NASA Technical Memorandum 4524

Flight Testing of Airbreathing Hypersonic Vehicles

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ABSTRACT

Using the scramjet engine as the prime example of a hypersonic airbreathing concept, this paper reviews the history of and addresses the need for hypersonic flight tests. It also describes how such tests can contribute to the development of airbreathing technology. Aspects of captive-carry and free-flight concepts are compared. An incremental flight envelope expansion technique for manned flight vehicles is also described. Such critical issues as required instrumentation technology and proper scaling of experimental devices are addressed. Lastly, examples of international flight test approaches, existing programs, or concepts currently under study, development, or both, are given.

1. INTRODUCTION

As mankind reaches out into space and develops the need for rapid global transportation over long distances through the atmosphere of the Earth, the technological need for hypersonic flight increases. Requirements that drive the desire for airbreathing hypersonic flight include quick, on-demand access to space with a payload and rapid access to distant points on the Earth. For commercial and military applications, these vehicle concepts seek aircraft-like operations, such as horizontal takeoff and landing and rapid turnaround capability to facilitate ground handling operations, minimize launch crews, and decrease flight infrastructure. Such vehicles must be reusable, reliable, safe, and cost effective to operate and must have minimal negative environmental impacts on the atmosphere.

Technologies for this class of vehicles have been under development for more than 30 years. Within the last 10 years, however, a recent world-wide increase in efforts to develop the first generation of truly operational vehicles has occurred. Such integrated hypersonic vehicles are extremely complex and costly and must operate in very hostile flight environments.

Developing and validating airbreathing hypersonic flight technologies and the requisite design methods requires carefully combining advanced analysis, ground test, and flight test. Analytical techniques and prediction methods are presently limited as design tools because they have yet to be fully validated at the necessary high Mach number operating conditions.

Airbreathing hypersonic systems, such as the scramjet, have operating ranges and requirements beyond those of present day ground test facilities. These facilities contribute significantly to developing the requisite technologies but are often limited in accommodating hardware systems and sizes; in available test Mach number ranges; and in properly simulating such flight conditions as Reynolds number, enthalpy, real gas, and ambient pressure. In particular, these technologies exceed facility capabilities for large-scale, integrated systems which require testing for long duration under real gas conditions.

The ultimate validation of any flight vehicle can only be achieved through careful flight testing to expand its operational envelope. Today, merely evaluating and confirming established or proven design methods and technologies, with full ground test simulation of the expected operating envelope, is not possible for this advanced class of airbreathing hypersonic vehicle concepts. Even the usual system performance criteria or evaluation specifications, such as flying qualities criteria, do not yet exist. These criteria and specifications must first be developed from flight research before being applied to future operational versions. Particularly in the case of hypersonic air breathers, flight provides the ability

to conduct research and to develop the needed technologies in real air under actual flight operating conditions. Flight is also the ultimate laboratory crucible for developing and validating as yet immature or unavailable design tools and methodologies.

This paper describes the need for flight research and how it can contribute to the development of hypersonic airbreathing technology. The scramjet propulsion concept is used here as a primary example. An historical perspective of hypersonic flight test development efforts and a look at how the results of ground tests and flight tests can differ are provided. In addition, analysis and measurement requirements for vehicle flight test are examined. Several international experimental flight test approaches are discussed by briefly surveying existing programs or concepts. An incremental flight envelope expansion technique for manned flight vehicles is also described.

2. HISTORICAL BACKGROUND

The dream of hypersonic flight dates back to the beginning of the 20th century. Around the time of World War I, such visionaries as the Rumanian Hermann Oberth, the American Robert Goddard, and the German Max Valier proposed concepts for rocket-powered space flight. In the 1930's, the Austrian Eugen Saenger studied the concept of a winged, rocket-powered space transportation vehicle which could boost to low Earth orbit, reenter the atmosphere, and land horizontally. Some of the earliest experimental work began in Germany under Wernher von Braun at the V-2 Peenemuende site during World War II. This A-series concept, based on the A-4 winged version of the V-2 rocket, used test vehicles ranging from small airborne drop models to the Mach 4, full-scale A-4b flight vehicle to develop the technology.

Beginning in the late 1940's in the United States, the X-series of aircraft pushed the rocket-powered concept to approximately Mach 6.5 with the X-15 vehicle (North American Aviation, Inc., Los Angeles, California) in the 1960's. During the 1950's and 1960's, this flight research was expanded with numerous other U.S. National Advisory Committee for Aeronautics and National Aeronautics and Space Administration (NASA) or U.S. Army and U.S. Air Force rocket- or ramjet-powered vehicles. These flight programs included the X-7 and X-17, Lewis Hypersonic Test Vehicle, Able Phase I, RVX-1 and -2 reentry vehicles, and many other testbed flight concepts. A number of these experiments pushed the explored flight envelope to hypervelocity speeds of Mach 14 and greater. Often motivated by national defense interests in developing ballistic missiles, these studies focused on aerothermodynamics, materials and structures, aerodynamics and rarefied gas dynamics, reentry flight mechanics, and ramjet propulsion performance.

Despite the ill-fated X-20 Dyna-Soar (Boeing Company, Seattle, Washington) project of the late 1950's and early 1960's, which was canceled in 1963, two subscale free-flight lifting reentry vehicles conducted successful flight test programs in the 1960's. From September 1963 to February 1965 atop Thor and Thor-Delta rockets, the joint U.S. Air Force and NASA Aerothermodynamic/elastic Structural Systems Environmental Tests (ASSET) (McDonnell Douglas Aircraft Corporation, St. Louis, Missouri) program flew 6 flights at altitudes from 168,000 to 225,000 ft and at speeds from Mach 13 to 19 (ASV1-4 and AEV-1 and -2). Figure 1 shows shows the ASSET vehicle configuration. Flight research focus included aerothermodynamics, structural concepts and materials, reentry aerodynamics and aeroperformance, and structural flutter dynamics. In addition, these vehicles had advanced guidance and control,

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airdata, instrumentation, and telemetry systems. These instrumentation and telemetry systems provided extensive data measurement.

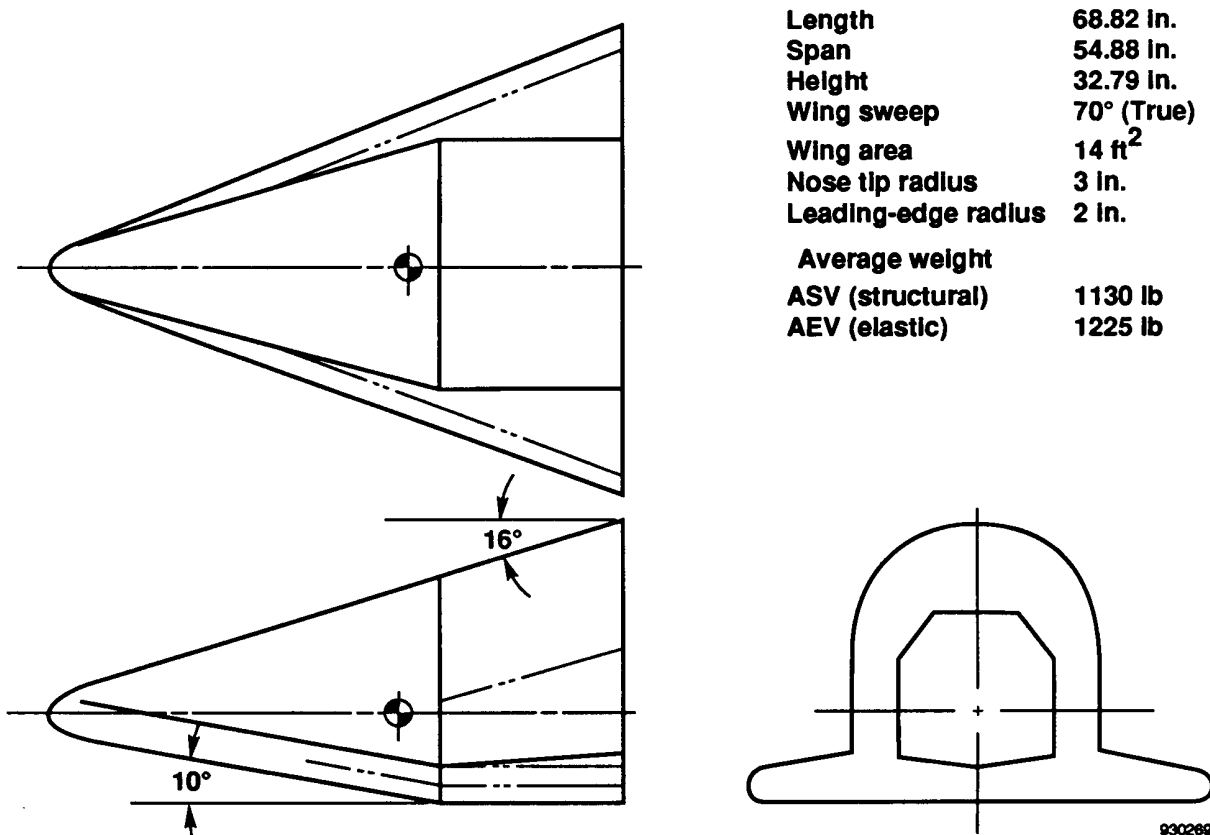|	
Length	68.82 In.
Span	54.88 In.
Height	32.79 In.
Wing sweep	70° (True)
Wing area	14 ft^2
Nose tip radius	3 In.
Leading-edge radius	2 In.
Average weight	
ASV (structural)	1130 lb
AEV (elastic)	1225 lb

Fig. 1. The ASSET vehicle configuration.

The second vehicle, a U.S. Air Force project called Precision Recovery Including Maneuvering Entry (PRIME), used the ablatively cooled SV-5D lifting body (Martin Aircraft Company, Baltimore, Maryland) (fig. 2) launched from atop the Atlas rocket. The primary objective was to study the flight mechanics and aeroperformance of maneuvering reentry with cross range. Secondary objectives involved aerodynamic and aerothermodynamic research. From December 1966 to April 1967, three test flights (FV-1 to -3) were flown from low Earth orbit to a splash-down water recovery. Only FV-3 was completely successful in this regard. Such successful unmanned lifting reentry vehicles as ASSET and PRIME were coupled with the M2 and HL-10 (Northrop Corporation, Newbury Park, California) and X-24B (Martin Marietta Aircraft Company, Baltimore, Maryland) series of lifting bodies for low-speed, low lift-to-drag ratio approach and landing tests to clear the way for the operational space shuttle vehicle of today.

The supersonic combustion ramjet, or scramjet, engine shows great potential for hypersonic air-breathing flight at speeds in excess of Mach 5. On the other hand, this engine has never been successfully flight tested in its operational hypersonic speed regime at Mach 6 and above. In the 1960's, two projects sought to develop scramjets in the flight test environment. One was the U.S. Air Force Scramjet Incremental Flight Test Program which planned to use a Castor rocket carriage vehicle. The second involved NASA Langley Research Center axisymmetric Hypersonic Ramjet Experiment strapped to the bottom of

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the X-15. For several reasons, these programs never reached the flight phase. Hallion (1987) provides excellent detailed technical descriptions and discussions of the history of these projects.

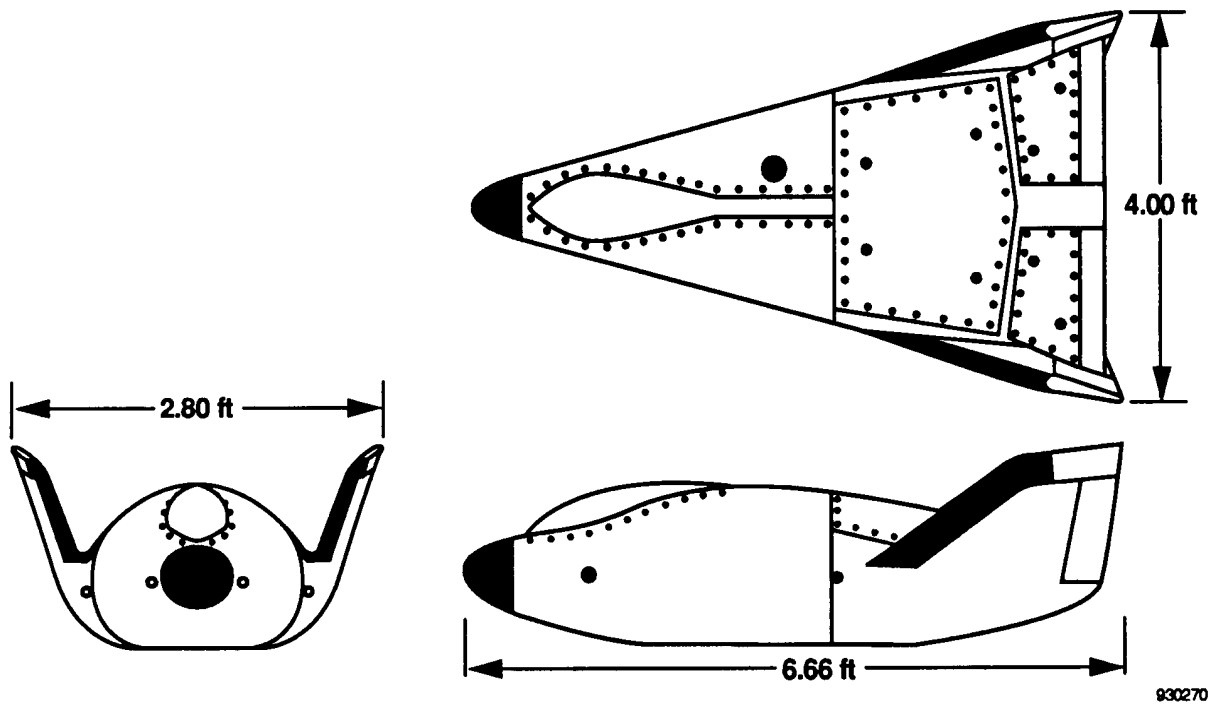**4.00 ft**

2.80 ft

6.66 ft

930270

Fig. 2. The SV-5D hypersonic research lifting body.

Recently, from 1987 through 1992, four Russian, dual-mode, scramjet flight tests were conducted to about Mach 5.5 at an altitude of approximately 85,000 ft. Only the last two tests involved actual combustion. Results indicate that short periods of supersonic combustion were achieved. Further details of this project are given in subparagraph 7.5. Presently, it is uncertain what future developments may be realized from this or other Russian programs.

3. FLIGHT TEST DEVELOPMENT OF HYPERSONIC TECHNOLOGIES

Scramjet-powered vehicles depend heavily on a very high degree of airframe integration. Such integration is needed not only to increase volumetric efficiency and minimize drag, as with typical aircraft, but also because a large part of the engine performance is derived from the airframe. Virtually the entire underside of the vehicle serves as the "engine" in a full nose-to-tail sense. Unlike turbojet compressors, the scramjet internal flowpath, by itself, is geometrically too simple to generate sufficient pressure rise for combustion without the forebody. Likewise, thrust-producing extraction of flow momentum in the exhaust is very inefficient with only an internal engine nozzle without a large external nozzle formed by the underside of the aft airframe.

Subsections 3.1 through 3.3 describe the hypersonic, scramjet-based, airbreathing, operating envelope and discuss the contributions and limitations of ground test techniques in addressing these conditions. Ground test limitations highlight those areas of technology where flight test is especially beneficial in developing the integrated vehicle concept and validating design methods. Flight test contributions are also described.

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3.1. Flight Operational Envelope

The hypersonic airbreathing flight regime is the most severe for any flight vehicle, including, for example, orbital reentry vehicles, which fly at comparatively low dynamic pressures (fig. 3). To produce sufficient levels of thrust, the hypersonic air breather must fly deep in the atmosphere at high dynamic pressures (for example, nominally 2000 lb/ft^2) to capture and process enough airflow. This high dynamic pressure, in turn, results in high aerothermodynamic heating and large structural airloads. Mach number ranges up to and including Earth orbital speeds introduce changing chemical and physical conditions on the airflow around the vehicle and through the engine. Such effects as chemical kinetics, flow ionization, and real gas changes on the ratio of specific heats from ideal air ($\gamma = 1.4$) and the air viscosity come into play because of the high speeds and temperatures generated. When encountered, such localized atmospheric effects as wind shears, turbulence, and density pockets can significantly affect flight vehicle performance and stability.

Flight testing a vehicle, its technologies, and its design methodologies can best be characterized using a design and operational state space concept. This state space consists of such subelements as the flight state, vehicle state, atmospheric effects, local flow conditions, and vehicle systems. Each subelement must be fully explored through a blend of ground test, flight test, and analysis to develop fully an operational vehicle.

The flight state is defined by vehicle velocity or Mach number and dynamic pressure conditions. Figure 4 shows a typical single-stage-to-orbit (SSTO) flight envelope. Ranges of dynamic pressure, total temperatures, and total pressures to be encountered are also shown. The flight envelope must be fully explored by the actual test vehicle, especially when ground testing cannot simulate the proper operating conditions with sufficient fidelity. The same is true for the vehicle state along its flightpath, which includes such items as angles of attack and sideslip, acceleration load factors, and flight attitude and rates.
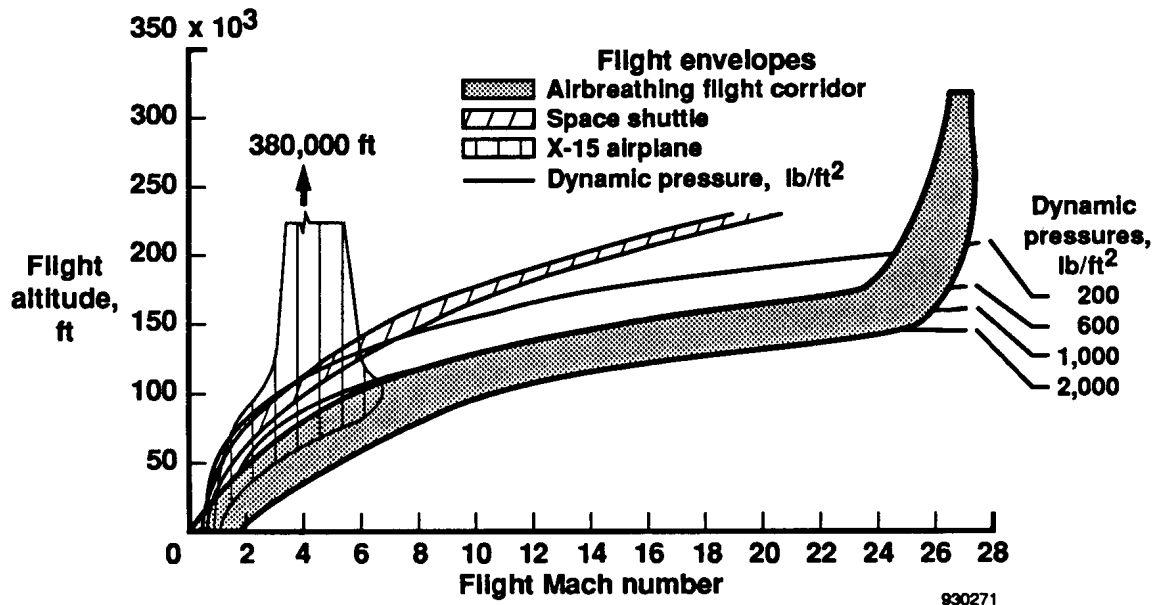

Fig. 3. Comparison of airbreathing and nonairbreathing flight corridors.
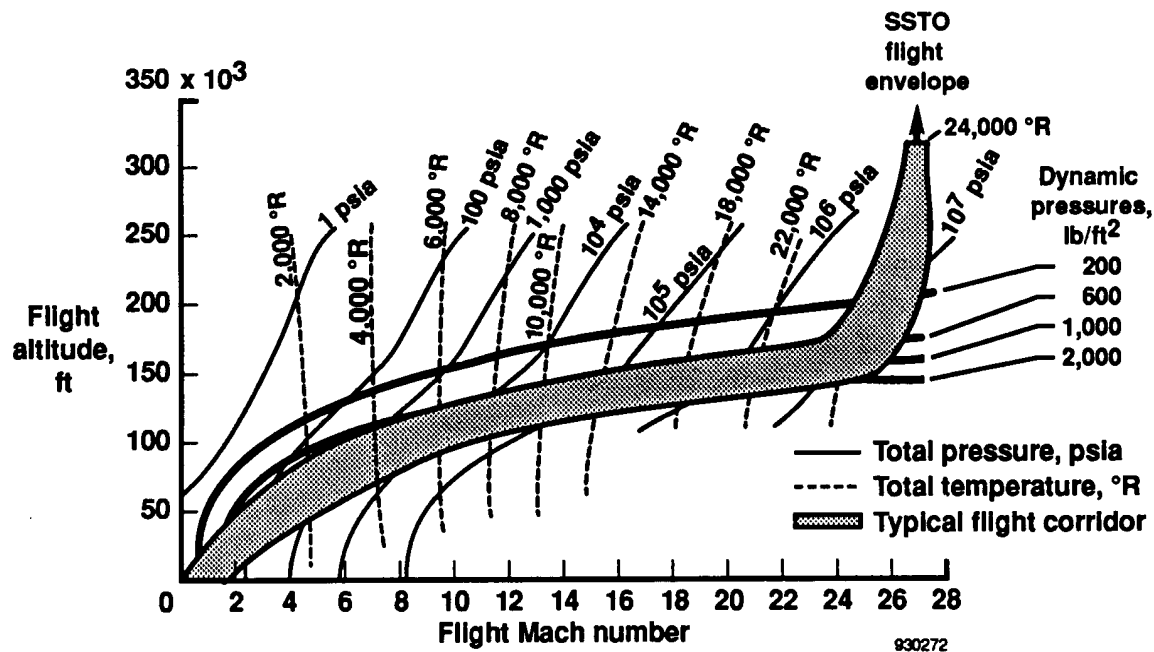
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Fig. 4. Typical hypersonic airbreathing flight corridor.

Figures 5 and 6 show the range of unit Reynolds number and free-stream enthalpy represented by the flight envelope shown in fig. 4. Both parameters are plotted as a function of free-stream Mach number with scramjet operable ranges of atmospheric dynamic pressure. Additionally, the free-stream enthalpy plot in fig. 6 shows the constant heat addition contribution of hydrogen combustion at a fuel equivalence ratio, ϕ, of 1.0. Note from the extreme aerothermodynamic conditions illustrated in figs. 4 and 6 that the operational environment requires significant development efforts in hot structure concepts and advanced materials to survive the thermal environment. Thermal stresses and materials effects impart unique characteristics and problems to these hot aircraft compared with the cold aircraft of today.

Isolating the scramjet engine from atmospheric environmental effects, angles-of-attack and -sideslip sensitivity, or other sudden changes in the flightpath is much more difficult to accomplish than is the case with modern turbojet engines. Atmospheric effects include air chemistry, humidity, and atmospheric dynamics. Atmospheric dynamics include turbulence, wind shears, and density gradients. Such local flow conditions as shocks, boundary layers, and base pressures must be properly generated or simulated and investigated to understand fully the performance sensitivity of the scramjet to the atmosphere. These effects, dynamics, and conditions must be addressed through flight test or ground test simulation.

Finally, the vehicle-technology state space is defined by the vehicle systems. Items to be addressed here include geometry as well as material and structural fidelity. Scale effects, including geometry and test time, are often important effectors in testing and validating requisite technologies. A build-up test approach moves from system components to integrated systems tests and includes ultimately testing the totally integrated flight vehicle. Various component and vehicle subsystems and controls must be incorporated and evaluated in the sequencing of ground and flight tests.

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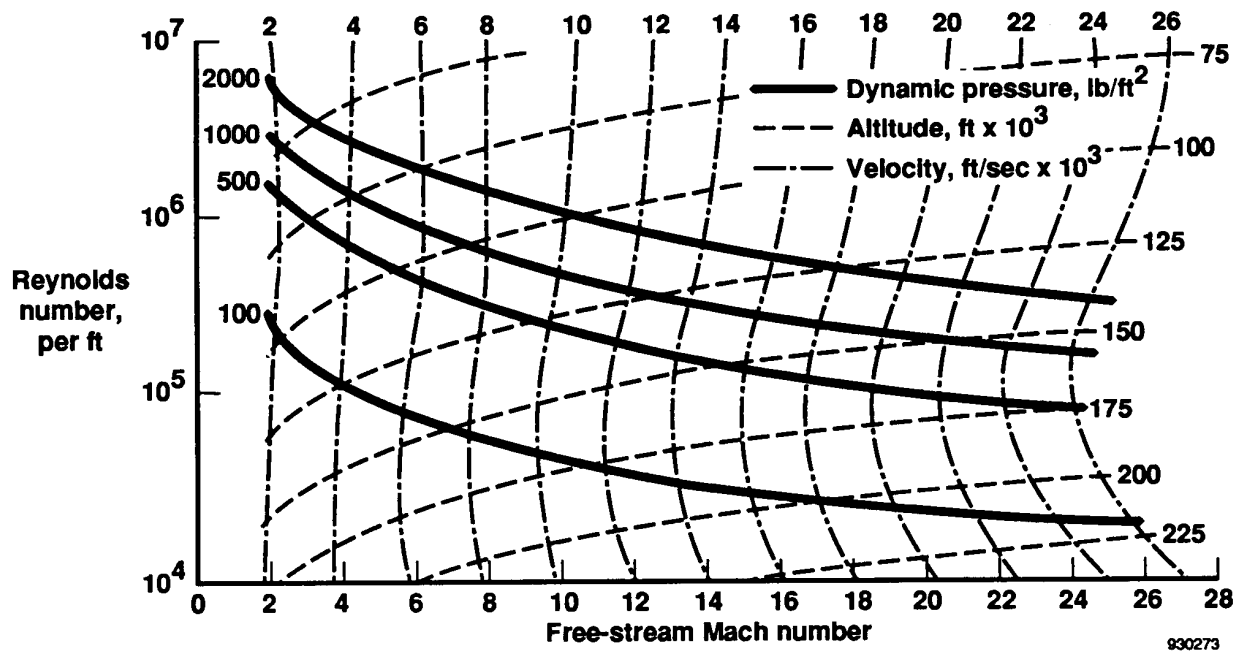
Fig. 5. Unit Reynolds number requirements for hypersonic flight conditions.
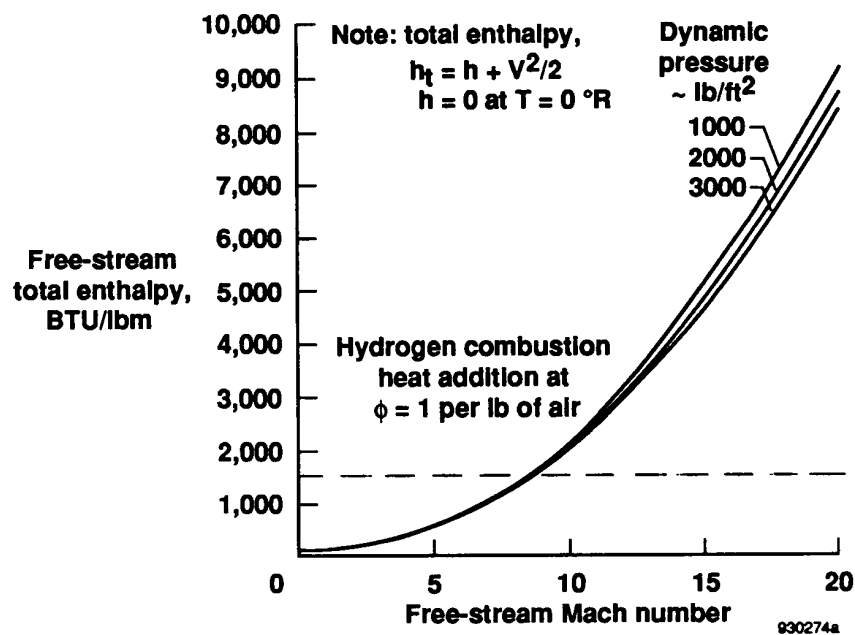
Fig. 6. Enthalpy as a function of Mach number.

3.2. Ground Test Facility Contributions and Limitations

Properly designed ground tests significantly contribute to successfully designing and developing flight vehicles. Often, these tests are the best methods of isolating and addressing technical problems or issues in a design through component tests or controlled experimental conditions. The results usually

form the genesis of databases and design tools, measurement and analysis techniques, and system design validations which lead to developing the integrated flight vehicle.

On the other hand, practical limitations encountered in ground test facilities and techniques are particularly troublesome in the hypersonic flight regime. Such practical hardware problems as inaccuracies of scale or size, lack of incorporating or simulating critical systems, and lack of properly represented system integration arise because of facility volume or other operational limitations. Other facility limitations also arise, for example, brief test duration (milliseconds in shock tunnels when seconds are needed) and limited Mach number ranges (a maximum of Mach 8 for long-duration wind tunnels). Often, real air cannot be simulated because of the need to test with other gases or to combustion-heat air for enthalpy simulation. Heating, in turn, results in vitiated air (in other words, air containing combustion products or contaminating particulates), or the chemical composition is otherwise changed because of oxygen depletion and make-up. Other test problems include accurate Reynolds number simulation; pressure, and temperature, or both, (enthalpy) simulation at high Mach number and dynamic pressure conditions; tunnel interference problems; and engine exhaust effects simulation. Figure 7 illustrates the problem for hypersonics by comparing the ground test facility test envelope capabilities with the desired flight operational envelope for an SSTO vehicle.

Fig. 7. Existing ground test capabilities for hypersonic development.
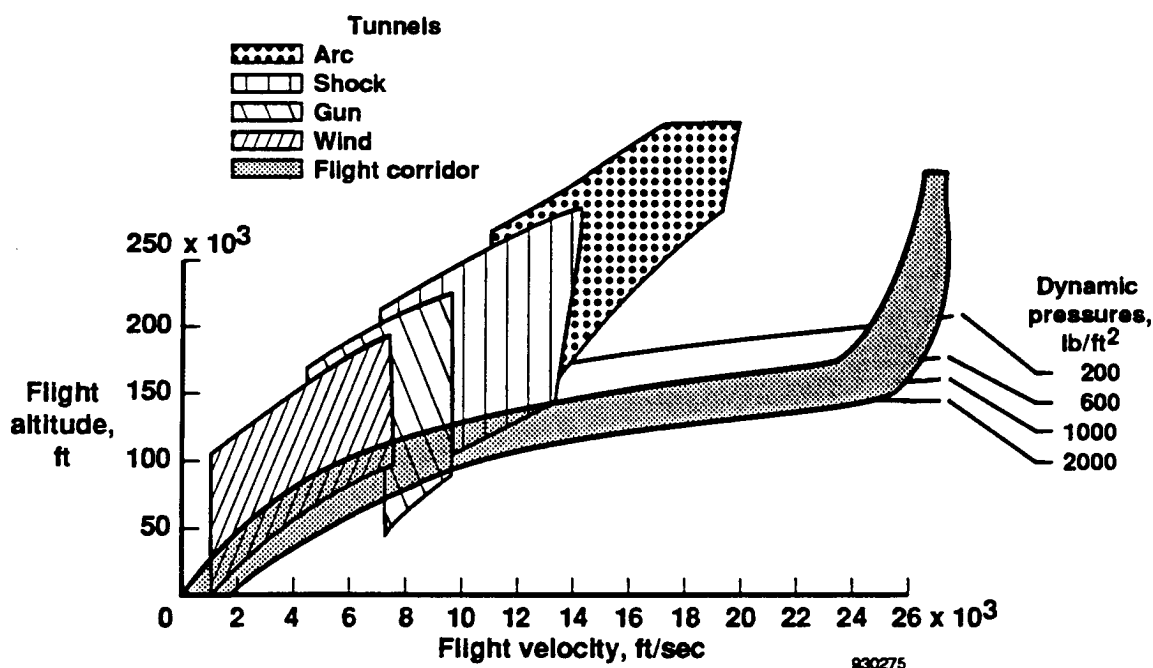
3.3. Flight Test Contributions

Flight test is the ultimate validation of a design or technology development process. This process is most often begun through predictive analysis and ground tests. The need for flight test validation is especially true of large, complex, integrated flight systems which frequently reveal some significant surprises in flight.

The large, delta-winged space shuttle orbiter provides an excellent example. This vehicle reenters the atmosphere of the Earth from orbit at severe aerothermodynamic conditions to a horizontal landing similar to an airplane. Several interesting mispredicted aerothermodynamic heating phenomena occurred on the early shuttle flights. Some of these phenomena were advantageous, others were not. Examples include reaction control system jet interaction effects on higher than predicted angles of sideslip during reentry, flow impingement angle-of-attack effects on orbital maneuvering system pod heating, wing leading-edge heating from boundary-layer and shock interactions, and predictions of thermal protection system surface catalysis heating effects on the lower side of the vehicle. Iliff and Shafer (1993) describe these phenomena, give other vehicle examples, and compare flight and ground test results.

Another shuttle example involves the effects of mispredicted boundary-layer transition on vehicle windward-side heating. Preflight analytical predictions and ground tests used smooth models as well as an assumed surface roughness to model boundary-layer transition location and time from initial reentry. Actual tile installation revealed that the resulting surface would be much rougher than modeled because of large gaps, unexpected rounded edges, and general surface unevenness from one tile to the next. Although some regions near the nose of the shuttle about the centerline were well predicted, the aft end of the vehicle was significantly mispredicted. Iliff and Shafer (1993) note that this misprediction was probably caused by wind-tunnel noise masking the modeled surface roughness.

Figure 8 shows that the transition was predicted to start at just over 900 sec into the reentry phase and then gradually move forward to the nose region. In fact, transition occurred much later than predicted and, once started, almost instantaneously propagated to the front of the vehicle. Figure 9 shows the net result—a delayed rise in surface temperature. In turn, this unexpected, advantageous effect resulted in lower surface temperatures and structural heat load than had been predicted.
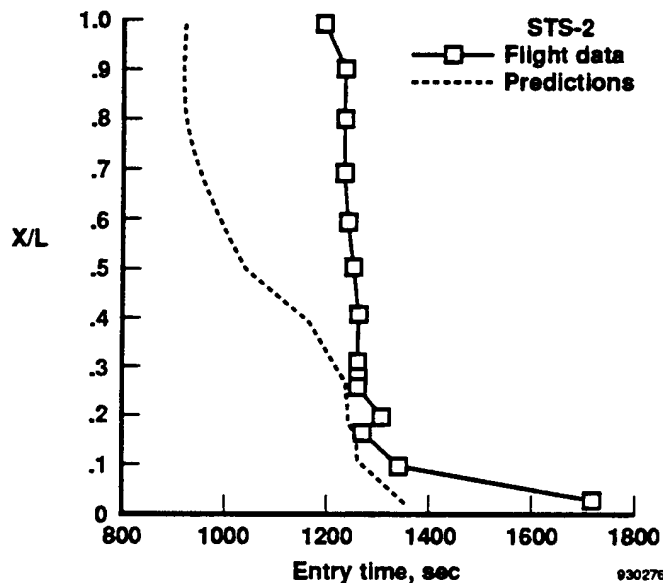

Fig. 8. Comparison of predicted and measured transition times for STS-2 (modified from Iliff and Shafer 1993).

Mispredictions could cause problems with structural and materials integrity or active cooling system performance because of higher than predicted surface temperatures and heat loads. Flight data from

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such cases can be fed back into the analysis and ground test techniques to improve future prediction and modeling methods.
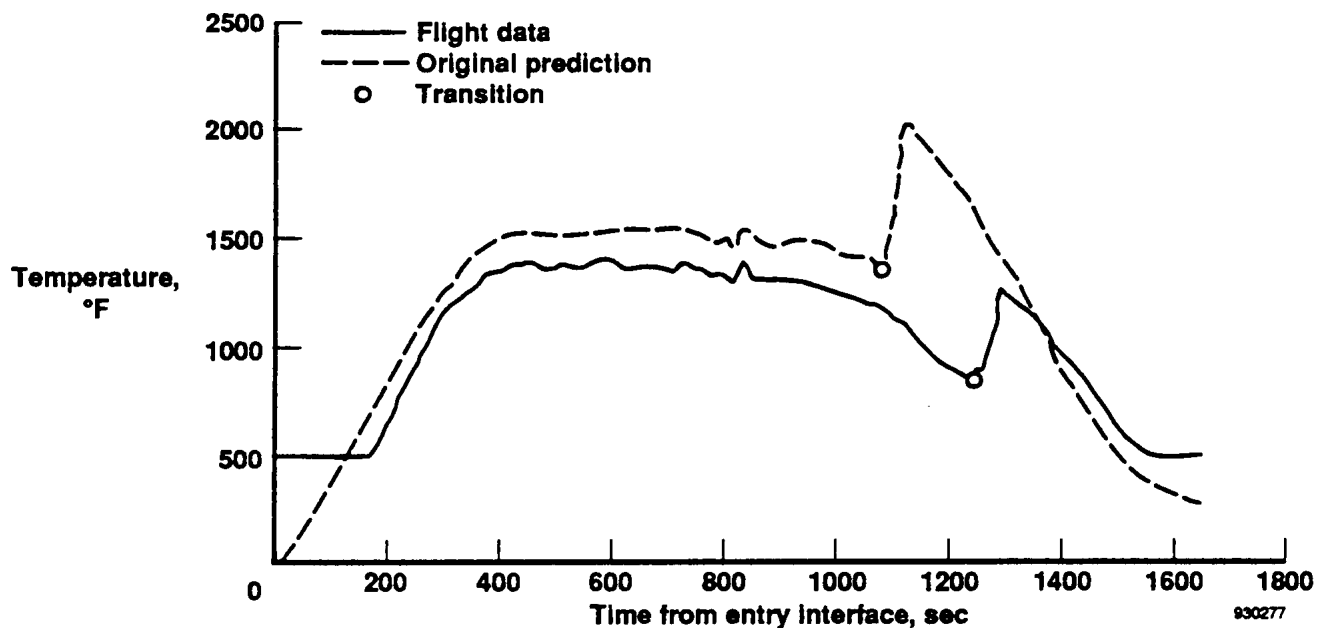

Fig. 9. Lower surface temperature comparison at X/L = 0.7 (modified from Iliff and Shafer 1993).

4. ANALYSIS AND PREDICTIVE DESIGN TOOLS VALIDATION

Developmental flight test aims to develop, validate, or both, mathematical analysis methods and other predictive design tools. Some design tools are based on physical and mathematical theory. Others are empirically derived models based on experiments which predict a phenomenon or estimate the system performance and operational characteristics. In either case, these analytical methods must be validated for the unique, extreme hypersonic flight conditions. These conditions include high temperature, high Mach number, and low-to-high-pressure effects not normally required of traditional airbreathing aerospace vehicle design tools. These methods must also evaluate complex geometry and systems for a complete, nose-to-tail analysis of the flight vehicle performance under conditions of engine combustion and reacting flows. Current computer codes or models are only valid for restricted flow conditions, for example, with no combustion physics; simplified geometries; or isolated vehicle components, such as the vehicle forebody.

A prime example of analysis methods validation is the set of Computational Fluid Dynamics (CFD) codes which are being developed for design of future hypersonic airbreathing vehicles. These codes are typically versions of the Navier-Stokes fluid dynamics equations which assume uniform, homogeneous flow with no chemical reaction or specie diffusion. Modern CFD computer codes have different analysis schemes. Such schemes include various time or space marching of the computations, geometry or spatial griding schemes, and methods of handling changing viscosity effects. Other recent computational features include embedded mathematical or empirical models to account for such effects as turbulence and chemical reactions. These powerful codes show great promise for computing full, three-dimensional, reacting continuum flows with viscous effects. Developmental problems to overcome include long, expensive computation time; complex, dense griding of the vehicle geometry and surrounding flow; and

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accurate representation of nonideal flow physics and chemistry. Specific validation objectives include checking the ability of the general Navier-Stokes equations to compute flows under high-temperature and low density conditions. Air chemistry changes from high gas temperatures include exciting atomic vibrational modes, molecular dissociation, and ionization. Results include chemical radicals, free atoms, and charged particles. Figure 10 shows that these effects, in turn, result in changing the perfect gas ratio of specific heat of 1.4 at ambient conditions to lower real gas ratios approaching 1.2 at 5000 °R (White 1974). In turn, these changes affect flow viscosity and reaction chemistry. Low density effects result in the need to analyze flow for noncontinuum effects. This need is not inherent in the theoretical basis for the Navier-Stokes equations.
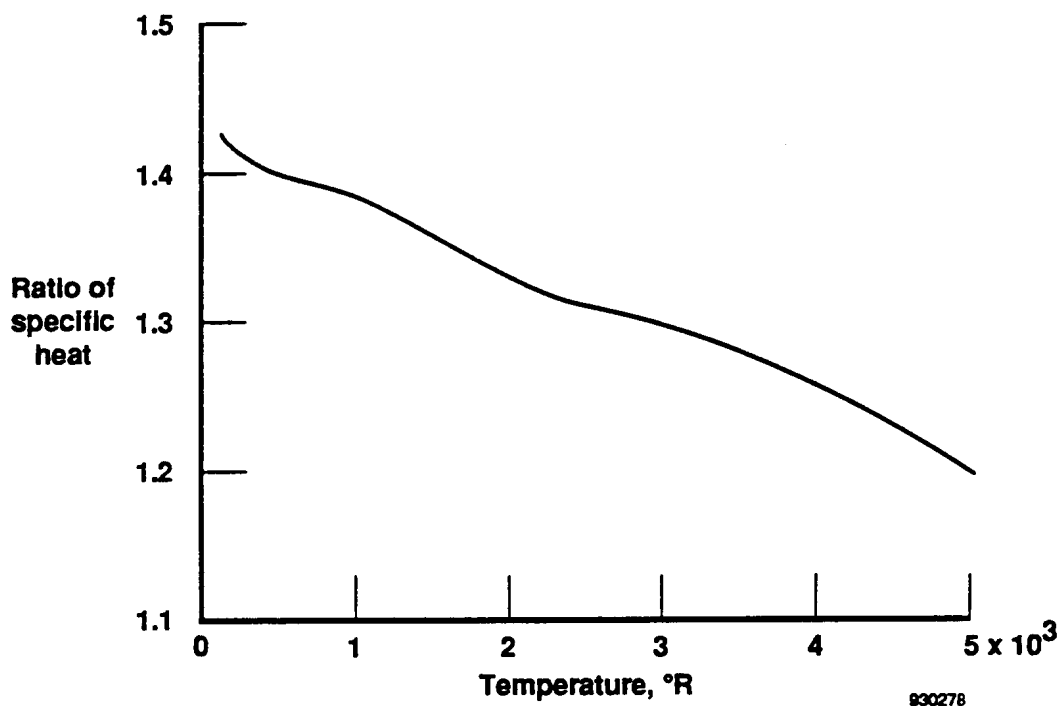
Fig. 10. Specific heat ratio for air (modified from White 1974).

Other flow complexities to be accounted for in CFD include viscous effects, such as low-momentum boundary-layer formation; shock boundary-layer interaction; and flow separation caused by large adverse pressure gradients, geometry discontinuities, or shocks. Additional factors for analysis will include accurate boundary-layer turbulence transition, correct turbulent mixing in the combustor, and vortical interactions. Such factors cause large flow pressure, surface friction, acoustic loads, and heat flux changes with direct effects on vehicle operation and performance. Shih and Neumann (1991), Marvin (1992), and Marvin (1993) give detailed descriptions of CFD validation issues and requirements.

5. FLIGHT TEST TECHNIQUE CONCEPTS

Subsections 5.1 through 5.4 examine possible flight test concepts for enhancing technology development using several approaches. These approaches include subscale captive-carry and air-launched free-flight concepts. Use of subscale hardware, its issues, and limitations are also discussed. The value of full-scale integrated flight vehicles is addressed.

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5.1. Subscale Captive Carry

Depending on the resolution of such issues as required hardware scale, needed degree of system integration, and desired aim-test condition achievability, many useful flight experiments can be conducted with small subscale devices in a captive-carry mode aboard flight vehicles.

As used here, the term captive-carry refers to an experiment package or testbed platform in which perhaps several experiments can be simultaneously mounted. The package or platform is permanently attached to its carriage launch vehicle. Then, the vehicle propels the package or platform to the experimental test conditions for a finite time. These flight experiments can complement and correlate with ground tests and can achieve such conditions as real gas effects or higher test Mach numbers that are not attainable on the ground. Carriage vehicles can vary from rockets to aircraft depending on the experimental device, test conditions, risk assessment, and degree of mission control needed.

Rocket launch vehicles usually cost less and provide a less risky approach to carrying experiment packages aloft than aircraft. These vehicles achieve significant lift weight and accelerate to very high hypersonic Mach numbers. An example is the Pegasus® Piggyback Experiment configuration (fig. 11). This joint Advanced Research Projects Agency (ARPA) and NASA Dryden program is being carried out with the Orbital Sciences Corporation, Fairfax, Virginia, using a NASA Dryden B-52B aircraft (Boeing Aircraft Company, Seattle, Washington) to air-drop the rocket from 43,000 ft at Mach 0.8. Curry, Mendenhall, and Moulton (1992); Noffz et al. (1991); and Noffz et al. (1992) report on current basic hypersonic experiments in data sensor technology; airdata measurement; and aerodynamics, aerothermodynamics, or both.

Disadvantages of rocket concepts often include a high degree of experiment integration requirement, autonomous control, limited number of missions and achievable test conditions, lack of recoverability and loss of the test payload, and flight along atypical (nonballistic) depressed trajectories. Increased payload complexity, system operation, and highly modified trajectory control systems result from these disadvantages. Such unmanned test flights are usually unrecoverable or are recovered using risky, complicated procedures. Recovery of the test component device is highly desirable for post-test inspection.

Aircraft captive-carry flight experiments are limited to approximately Mach 3 and below. Figure 12 shows the NASA Dryden SR-71A testbed aircraft (Lockheed Advanced Development Company, Burbank, California). This aircraft testbed has been under study to conduct large-scale external burning tests for base-filling drag reduction to Mach 3 (fig. 13). Hicks (1992) provides further discussions of this concept.

Advantages of using aircraft instead of expendable rocket launchers center on mission flexibility to control the experiment, maximize success by flying to precise aim-test conditions, adapt to changing mission conditions, modify test objectives in-flight, cover multiple test conditions simultaneously in a given flight, and recover the experimental package for post-test inspection and reuse. Aircraft also carry large-to-full-scale devices, highly integrated systems, or both, aloft for maximum test fidelity.

® Pegasus is a registered trademark of Orbital Sciences Corporation, Fairfax, Virginia, but this vehicle was developed as a joint private venture between Orbital Sciences Corporation and Hercules Aerospace Corporation, Magna, Utah.

Disadvantages of using aircraft include high cost resulting from complex experiment package integration and accompanying extensive aircraft modifications, flight and range operation expenses, and high flight safety requirements for a man-rated system. Flight certification and clearance for such tests can be very involved, drawn-out affairs which result in added program cost and time.
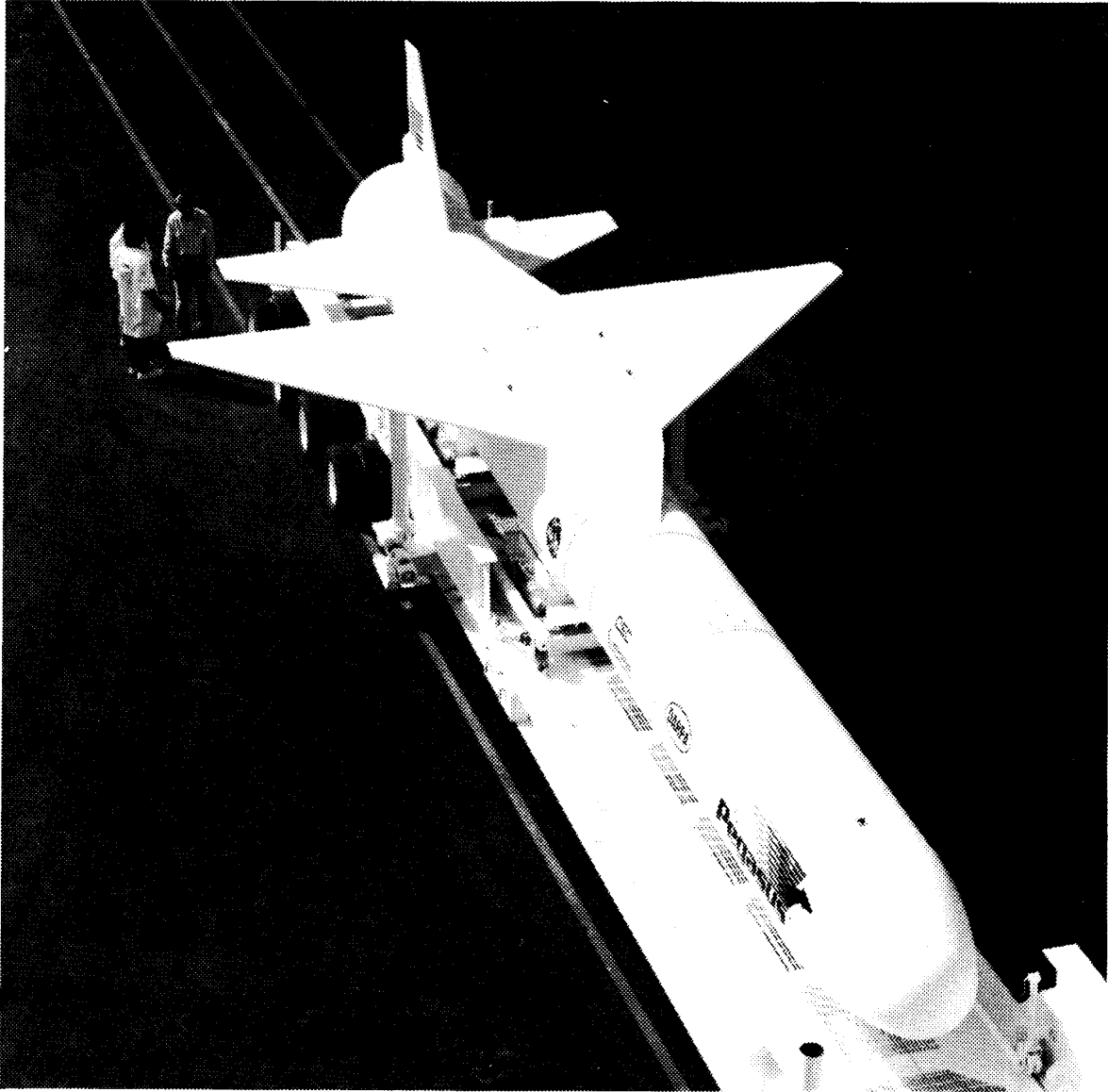
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Fig. 11. The Pegasus Piggyback Experiment configuration.
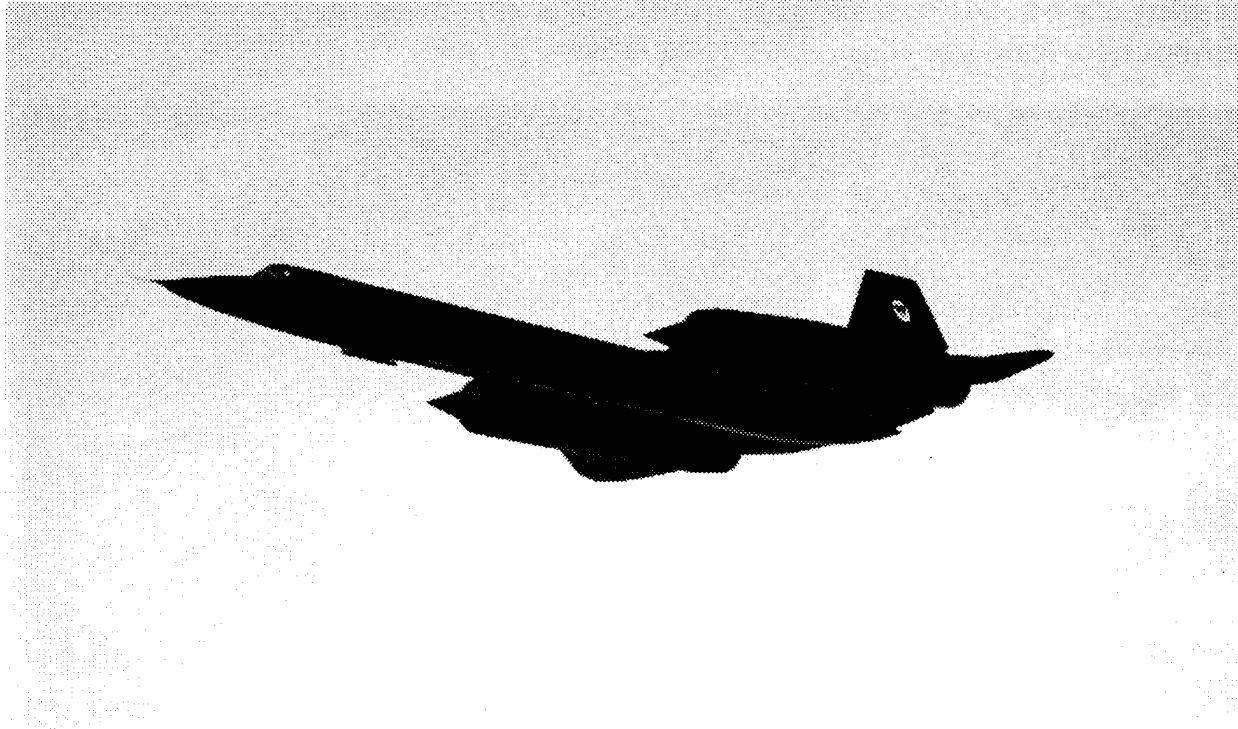
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Fig. 12. The SR-71A testbed aircraft.

10.81 in.

6 ft
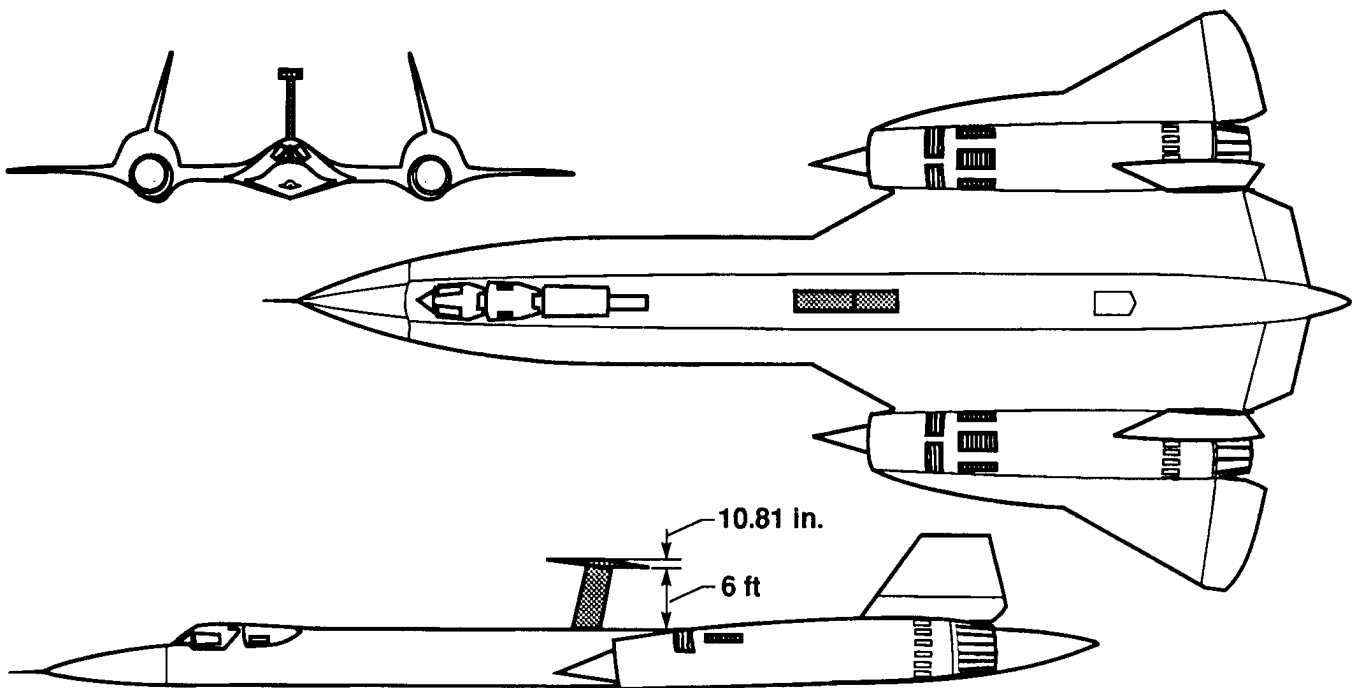
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Fig. 13. Experimental external burning aircraft model mounting.

5.2. Air-Launched Free Flight

Air-launched free-flight experiments are especially valuable for testing large subscale, highly integrated systems or complete flight vehicle concepts. Ultimate system or vehicle performance and proof-of-concept demonstration can best be achieved by free flight. Free flight is defined here as the experimental package or testbed platform which is separated or launched from a carriage vehicle to fly to and operate independently at the aim-test conditions.

The value of a free-flight device can be seen, for example, in demonstrating and measuring thrust production in a high speed (Mach 6 and above) scramjet. A free-flight vehicle allows direct assessment of the net thrust minus drag production without being encumbered by additional carriage vehicle drag; control requirements; and aerodynamic or structural interference, or both, from the launch vehicle. Launch vehicle integration may still be as or more complex than that of captive-carry experimental devices. On the other hand, operation and control can be simplified using the nominal trajectory sequence of the launch vehicle, such as the normal low dynamic pressure ballistic flightpath of a rocket. The control and maneuvering burden of flying at the desired deep atmospheric trajectories for airbreathing performance can then be placed on the experimental free-flight vehicle.

Given sufficient volume for a crew station and for control functions, test vehicles could be piloted, which increases flight safety, mission flexibility and experiment control, and recovery of the experimental vehicle. This capability is particularly valuable from a concept development point-of-view if the man-machine interface technology needs for an operational vehicle are required. For developmental purposes, however, a manned system should not be considered a requirement. The negative side of such man-rated systems is that vehicle costs for added systems and complexity as well as for flight certifications, systems, and operations can be quite high.

Careful consideration must be given to the desired end-launch conditions for the flight experiment. Large, integrated, free-flight vehicles could be launched at subsonic-to-supersonic conditions and then accelerated to the aim hypersonic test conditions. Figure 14 shows the mothership, NASA Dryden B-52B. This mothership can air-launch X-15-sized vehicles of up to 25,000 lb and 50-ft long from a wing pylon at approximately Mach 0.85 and from an altitude of 40,000 ft. The NASA Dryden SR-71A testbed vehicle can air-launch experimental 20,000-lb, 60-ft long vehicles at speeds of approximately Mach 3 at altitudes of approximately 85,000 ft.

Figure 15 shows the NASA Shuttle Carrier Aircraft (SCA) air-launch platform. This platform is similar to a 747 (Boeing Aircraft Company, Seattle, Washington) and can launch very large experimental vehicles of from 150,000 to 200,000 lb, at approximately Mach 0.6, and at an altitude 25,000 ft (Fulton 1977). Issues of an appropriate testbed center around the size and weight of experimental flight vehicle and on the desired launch energy and aim-test condition. For example, in the latter point, supersonic launch conditions of approximately Mach 3 would be needed to start and test a ramjet engine. This need could, of course, be achieved by accelerating to the Mach 3 aim-start condition with a rocket if vehicle size, weight, and integration could be accommodated. Such a supersonic launch point could also save the experimental vehicle acceleration fuel and result in significant savings in size, launch weight, and total fuel load to reach test conditions.
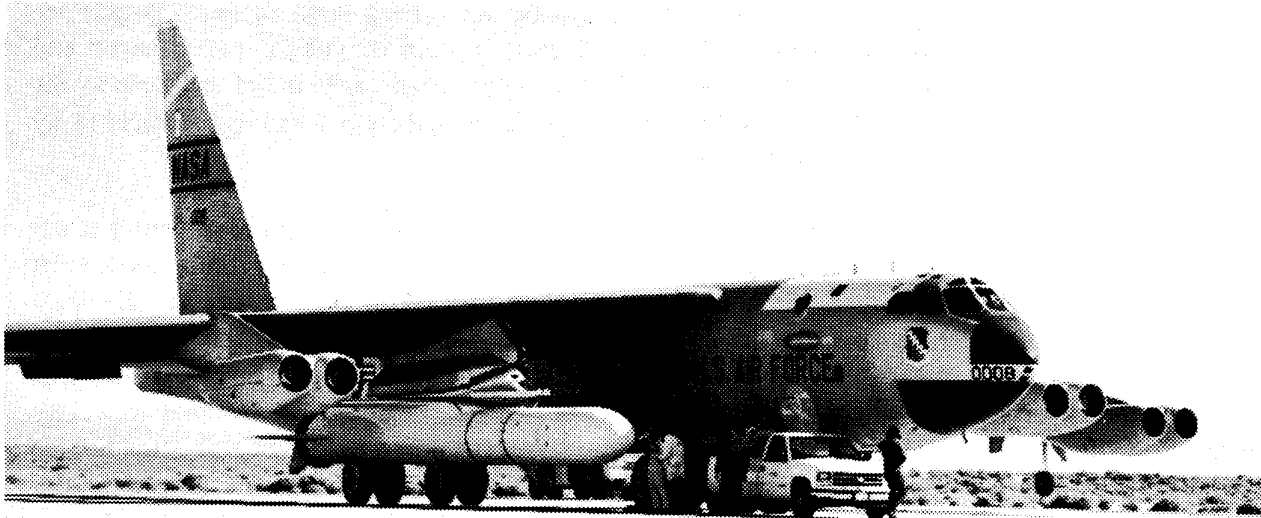
Fig. 14. The B-52B aircraft.
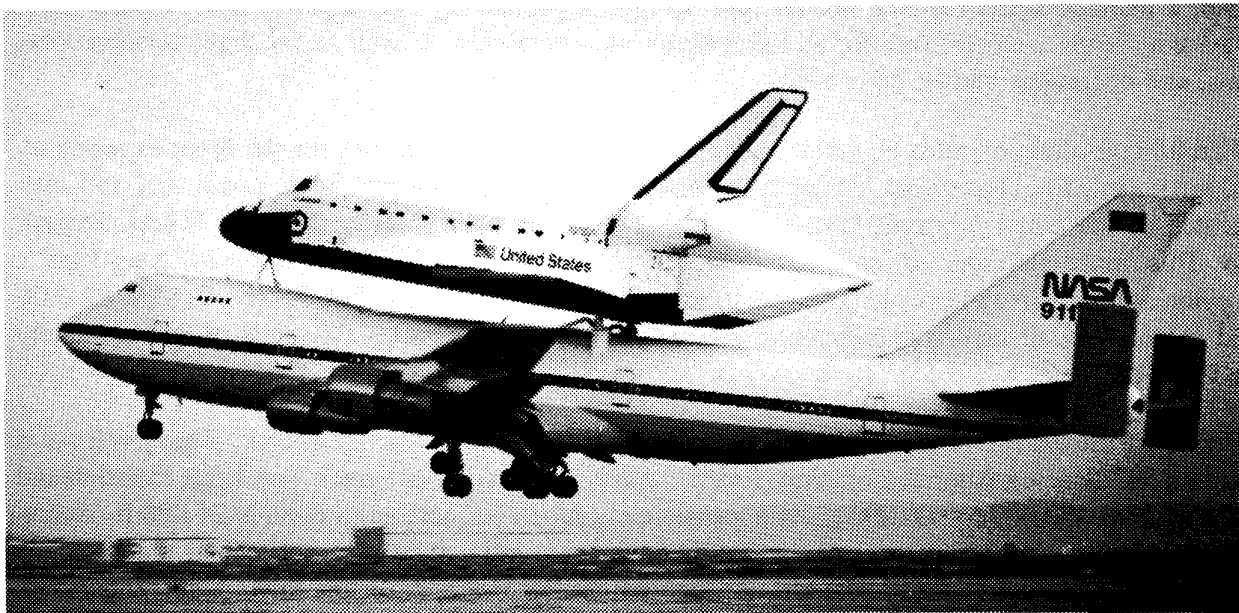
Fig. 15. The NASA Shuttle Carrier Aircraft air-launch platform.

5.3. Scale Selection

To be successful, results of subscale flight experiments must apply to final, full-scale devices. This application of results includes not only the question of viability in validating a scaled-down version of

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a given system design, operation, or both, but also in developing and validating design analysis tools, ground test methods, and measurement techniques. At best, the flight data product should directly apply to the full-scale system. As a minimum, through analysis and other means, the product should be useful when extrapolating to the desired full-scale results. In any case, subscale flight data are valuable for validating design and analysis tools, developing some phenomena modeling, and studying certain aspects of the physical system behavior. This approach, in turn, requires initial experiment design analysis and sensitivity studies to quantitatively assess proper scale and system fidelity before the subscale flight experiment is fully developed.

Examining the difficult subscale scramjet case illustrates the importance of scale selections. Adequate test scale of a scramjet design has been debated for many years. The basic issues to be resolved include engine flowpath physics and chemistry fidelity, engine design features to be incorporated or the degree of system operation mechanization desired, and system component fabrication and mechanization. These issues are briefly examined in sub-subsections 5.3.1 through 5.3.3.

5.3.1. Flow Physics Fidelity

Reproducing the proper flow physics and chemistry is the greatest technical issue for a subscale scramjet experiment. The expediency of using subscale devices can mask or totally miss simulating key flow parameters which affect system operation and performance fidelity. Figure 16 shows that engine operation begins with the flight vehicle forebody compression process ahead of the inlet where Reynolds-number-regulated viscous effects begin to develop the inlet boundary layer.
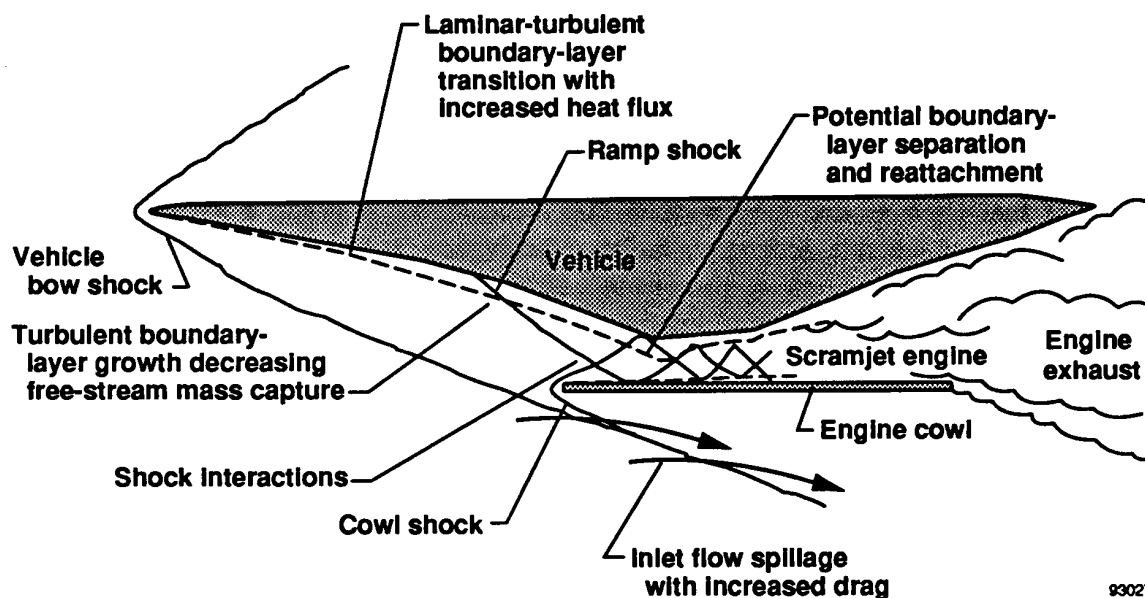
Fig. 16. Scramjet scaling issues.

Proper boundary-layer transition from laminar to turbulent flow conditions must be correctly located and accurately achieved to simulate the right level of heat flux, friction drag on through the engine, and boundary-layer displacement thickness and turbulent velocity profile at the inlet entrance. Forebody shock patterns and compression performance must also be duplicated, positioning shocks to avoid boundary-layer separation in the inlet and shock interaction effects on flow distortion and losses. The

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compression process; boundary-layer conditions; inlet-combustor component isolator function, if used; and system of generated and reflected shocks must also be accurately simulated through the inlet to the combustor entrance. As with many other influences, these shocks are propagated downstream and affect the rest of the engine operations. Leading-edge radii of cowl lips, struts, and other inlet components must be considered relative to simulating proper heat loads, shock formations, and drag. These elements can affect inlet kinetic energy efficiency, which is a component performance measurand.

5.3.2. Combustor Operation Mechanization

In the combustor, concerns regarding scaling issues include the combustor burning length. In turn, this length involves combustion dwell or residence time for proper chemical kinetics simulation and adequate fuel-mixing length. Chemical kinetics can be scaled to a limited extent in the combustor and nozzle by combining the correct length and static pressure. First, analysis must be performed to assess to what degree this combination is achievable for a given test configuration. Additional concerns include combustor skin friction and other drag sources; wall film cooling, if used; and internal static pressure, temperature, and local flow Mach number.

Injection fuel temperature can also be a key issue, especially if regenerative cooling with fuel is used. Inability to simulate the desired injection fuel temperatures (for example, the autoignition temperature of 1800 °R for hydrogen) can cause fuel ignition delays. It can also affect reaction rates, impact fuel and air shear-mixing effects, and impact fuel thrust adversely. The nozzle expansion process must, likewise, correctly simulate chemical kinetics and skin friction as well as external base pressures.

5.3.3. Hardware Fabrication and Mechanization

Once proper flow physics has been resolved, practical engine fabrication and integration must be addressed. First, engine component geometry relationships must be maintained, but a limit to size manufacturability and to operational mechanization and control exists. Examples include the diameter or slot height of fuel injectors and the flow insertion mechanisms, if used. This limit also involves flameholding devices and variable-geometry simulation, activation, and position sensing, where applicable. Other mechanical insertions, retractions, or both, of an instream device may be involved. Selected critical engine subsystems, such as pumps, control sensors, and actuators, may also be included.

Other issues include system volume adequacy for active internal structural cooling, instrumentation installation, and volume for such engine subsystems as control actuators, sensors, and pumps. If actual flight materials are not used, then substitute materials must be structurally, chemically, and thermally comparable. Ground test requirements for flight-to-ground data results correlation must also be included relative to the available ground test facilities and conditions. Finally, minimum performance levels desired must be considered to properly evaluate a design or demonstrate its operation or capability.

5.4. Integrated Flight Vehicles and Envelope Expansion

This concept for a large, integrated, aerospace plane flight test program is based on a conservative, incremental approach to expanding its operating envelope. The approach emphasizes flight safety and careful exploration of the integrated technologies. This perspective assumes that these first generation vehicles will, for the most part, explore new, unknown territory in the flight regime as well as in the

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integrated technologies and systems. As a result, program risk will be high, vehicles and flight facilities will be limited and expensive, and operational issues will be complex.

Conceptually, the flight test program could consist of two major phases. The first phase could expand the flight envelope to near the vehicle operating limits. The second phase could involve more dedicated flight research than the first. The flight envelope expansion phase would complete a functional check of the aircraft systems, validate system performance and operating characteristics, and define vehicle operating limits and anomalies. This vehicle flight clearance and system flight certification would include the airframe structure, engines, controls, and subsystems and collect a limited amount of flight research data. Once the flight envelope is cleared, the dedicated flight research phase would be flown within that envelope to investigate specific research objectives.

The flight envelope expansion program could be implemented on the basis of key flight clearance milestones. For example, the separate engine operating modes could be used, and each new test could be keyed to the engine mode transition points. This concept is a strong function of the specific vehicle configuration and characteristics and may need to be modified on the basis of controls or structures milestones. The incremental method would either proceed piecemeal directly along the design mission trajectory, such as an SSTO profile, or could approach that trajectory in a build-up fashion from off-design flight conditions, such as low dynamic pressure (high altitude) conditions.

The basic idea of such a flight envelope expansion program is to operate from and return to a single test site. This procedure maximizes flight safety and simultaneously eliminates or minimizes the need for multiple test sites with the attendant expensive duplication of ground facilities. The aircraft would accelerate and cruise outbound at an already cleared airspeed. Next, it would turn and accelerate to the new aim-clearance Mach number while returning to the recovery site. If problems were encountered at the newly expanded envelope point, then the vehicle could be safely powered down and returned to the landing site in the power-off or glide condition. An auxiliary rocket engine mode could assist in the acceleration to test conditions, if needed. The wings-level stabilized flight condition would be used to obtain the necessary flight clearance data at the new aim Mach number. Then, the aircraft would decelerate, return to the recovery site, and land.

For a vehicle operating out of Edwards AFB, California, the flight corridor would be over land with the maximum available test range or, at least, within landfall from over water (fig. 17). A safe landing could always be achieved. At speeds up to Mach 3, flight testing would be completed within the local area. For high Mach numbers of approximately Mach 12 and above, the flight corridor would extend outbound using the same basic flight profile. This flightpath extension allows the aircraft enough ground-track distance to accelerate to the aim conditions, stabilize for up to 1 min, and then decelerate and return to the recovery site. Once the ground track was insufficient for vehicle acceleration to test conditions, the flightpath could be reoriented to take maximum advantage of the available landmass. This process would continue until the maximum operating conditions were reached or insufficient landmass was available at these high hypersonic Mach numbers for a safe recovery. Then, in the case of an orbital vehicle, the vehicle would have to accelerate to orbit.
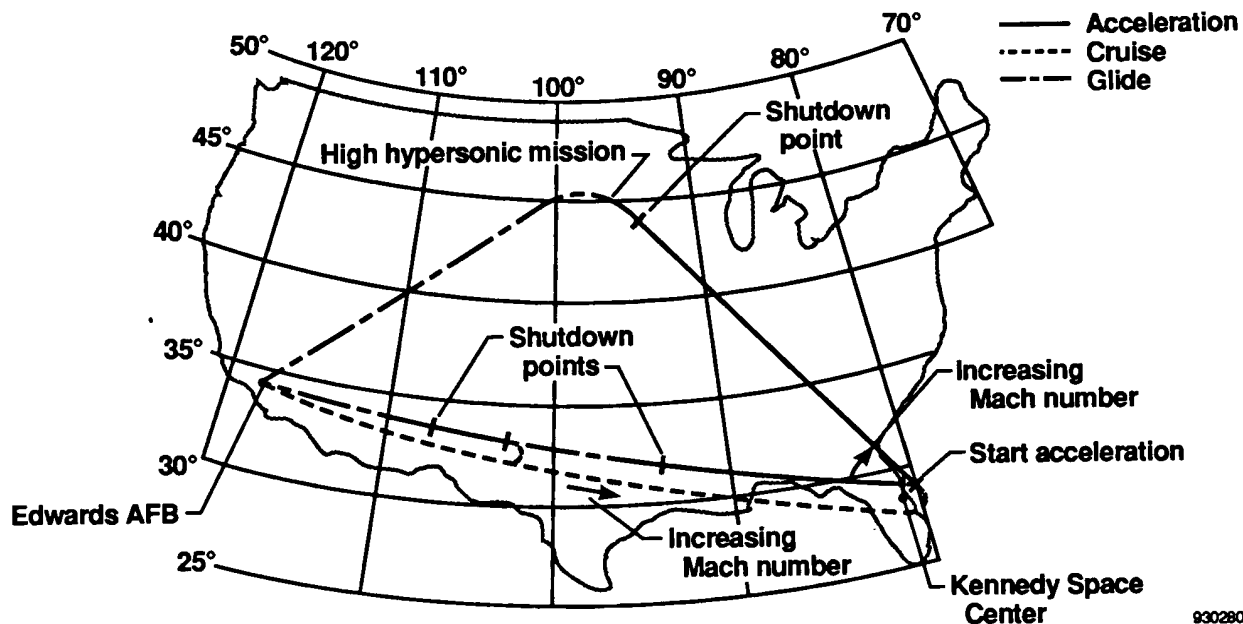
Fig. 17. Ground tracking of flight envelope expansion missions.

6. INSTRUMENTATION REQUIREMENTS AND STATE OF THE TECHNOLOGY

Flight instrumentation systems for hypersonic airbreathing vehicles have lagged behind the development of other requisite technologies. Bogue and Erbland (1992) note that because of the speed range involved and the extreme thermal and pressure flight conditions, instrumentation systems have had new demands placed on them. These systems include data acquisition and conditioning, recording, interconnects, telemetry, and transducer technology. Above all, the fundamental flight system requirement is that the flight instrumentation package, relative to ground test systems, must be as compact, lightweight, and rugged as possible to function in and survive the flight environment. Because the instrumentation system is potentially the highest maintenance and checkout component for aircraft operability, desired measurement sensitivity will have to be balanced with a high degree of system robustness to ensure reliability and maintainability.

The ground test system must have strong commonality with the flight test system for a given technology development effort. That is, the type, number, location, and distribution density of the transducer and the data processing system must be considered simultaneously, so critical data correlations can be made.

Measurement data quality for defining system design specifications and performance criteria must be addressed. In many cases, either because of the new, severe operating environment or the fact that many of the transducers are now being developed, adequate criteria and calibration methods do not yet exist. These criteria and methods must be established through experiments before they can be applied.

Subsections 6.1 through 6.5 give an overview of the instrumentation operating environment and data acquisition requirements. Examples of transducer development and some of these unique challenges are given for hot structures strain gages, instream flow-field measurement methods, and airdata techniques.

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6.1. Data System Operating Environment

The data system operating environmental challenge includes such factors as severe temperatures. These temperatures induce chemical, physical, or both, changes in transducer systems and the supporting structures and affect accuracy and life cycle operability. Other environmental challenges include high heat flux of up to 90,000 Btu/ft^2-sec (especially with localized shock-surface interactions), high-intensity acoustic fields of up to 200 dB, oxidizing or reducing atmospheres, and ionized plasma gas conditions. Such environmental effects introduce chemical, mechanical, or electrical changes in the operating environment and data system components. In turn, these changes affect the installation, component make-up, and operation. Local high-temperature flow fields about the flight vehicle induce gas ionization and dissociation, thereby creating a conductive plasma condition which affects transducer operation.

Instrumentation system design must account for operating in very hot environments ranging from heated external vehicle surfaces of up to 2000 °F to hot internal airframe compartments of, perhaps, 500 °F to internal engine stagnation temperatures which approach or exceed 5000 °F. Surface heat flux without shock interactions would nominally be up to 2000 Btu/ft^2-sec but could approach 5000 Btu/ft^2-sec at certain stagnation regions. New, advanced materials to handle the aerothermodynamic environment require new transducer installation techniques, especially with such advanced materials as metal matrix, carbon-carbon, carbon-silicon-carbide, and ceramic composites. Using several different structural materials in differing parts of a vehicle means facing different thermochemical environments and structural design concepts. These concepts affect installation techniques as well as calibration and measurement compensations. Additional application problems include surface attachment with advanced, high-performance adhesives and drilling holes through the materials for transducer installation without compromising material, structural, or active cooling integrity.

Of course, any thermal, electromagnetic, chemical, or mechanical interactions of the installed transducer must be minimized or accounted for to avoid affecting the quantity that is being measured. For example, the surrounding structure material stiffness, yield strength, and creep at high temperature affects transducer installation. Differential expansion caused by different thermal coefficients among the surrounding structure, transducer, and attachment medium can induce falsely sensed strains. These strains would require development of temperature compensation calibration techniques. Transducer integration must include consideration of small components that are chemically nonreactive and, once embedded in the surrounding structure, are a close enough physical match to avoid affecting the measurements.

Transducer survivability in thermochemical environments becomes a major question to be addressed. The need for transducer cooling or placing them in a thermally controlled environment adds weight, volume, and system complexity to the flight vehicle. The need for intrusive versus nonintrusive sensors for a given application, such as flow-field sampling, must be addressed.

6.2. Data Acquisition Challenges

In addition to advanced transducer development, equal attention must be given to developing the data processing and transmitting system if the measurement information is to be truly useful. Data processing and signal conditioning systems must be adapted to, perhaps, very large aircraft that often require thousands of parameters to be measured at very high sample rates. Some of these parameters are also used in vehicle flight avionics and other control functions, so they must be compatible with the

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normal aircraft operational systems. Onboard computers may be necessary to sort and reduce the data measurements, perform second or third generation computations on the measurements, and distribute these computations to several subsystems, including telemetry downlink.

Air-to-ground telemetry problems to surmount include antenna location and survivability under extreme aerothermal conditions. High data transmission rates in the several megahertz range coupled with a large number of parameters sampled over a wide frequency range to very high levels (thousands of samples per second) may require extensive data compression and multiple data downlink paths with ground-based data reconstruction. Data transmission through potential vehicle plasma sheets, vehicle tracking, and signal acquisition and relay over large ground tracks at high speeds needs to be resolved. Possible approaches include global-positioning satellites or an approach similar to the NASA Tracking and Data Relay Satellite System.

In vehicles where volume and weight become critical because of vehicle size or mission goals, the question of using collocated or distributed instrumentation system components arises. If sufficient volume is available, collocated systems are easier to integrate and operate. Nevertheless, long, large metallic wiring bundles from individual transducer groups to the data processing units are heavy and may also be limited by available routing volume. One approach uses sapphire or coated silica fiber optics which operate at temperatures up to 2000 °F to replace the wire bundles with lighter, more compact data transmission lines.

Distributed system components located nearest the respective transducer sets may be the best approach to shorten wiring and decrease system complexity if sufficient volume and cooling needs can be met in those areas. If the electronic components require environments similar to room temperature, then the compartments may require special cooling. Otherwise, data processing units with the ability to operate in high-temperature environments must be developed.

6.3. Hot Structure Strain Gages

New measurement transducer technology is in a state of high flux. Hot structure strain sensing using surface-mounted resistance strain gages or remote-sensing techniques provides an excellent example. Williams (1992) reported on noncontact remote sensing. This report describes research into such concepts as laser speckle strain measurement, phase-shifting interferometry, and X-ray extensometry. Another area involves high-temperature resistance strain gages. For example, palladium-chromium (fig. 18) or iron-chromium-aluminum gages, and advanced attachment and calibration techniques are being developed and ground tested to temperatures of 1000 to 2500 °F (Lei and Williams 1990; Holmes and Moore 1992; and Lemcoe 1992).

Figure 19 shows one of the hot structure strain gage development problems known as apparent strain. Thermal coefficient of expansion differences between the structure being measured, the strain gage, and the attachment medium induce false strain levels. Material phase changes within the gage also contribute to this erroneous or apparent strain level. This problem is especially acute in the iron-chromium-aluminum gages. Actual strain levels caused by load are typically 100 to 2000 μstrain. Actual strain can be highly distorted with apparent strain errors of up to 14,000 μstrain at temperatures approaching 1500 °F. Temperature compensation techniques are being developed by electrical resistance, calibration correction, or both, methods under thermal cycling to correct for these errors. This figure

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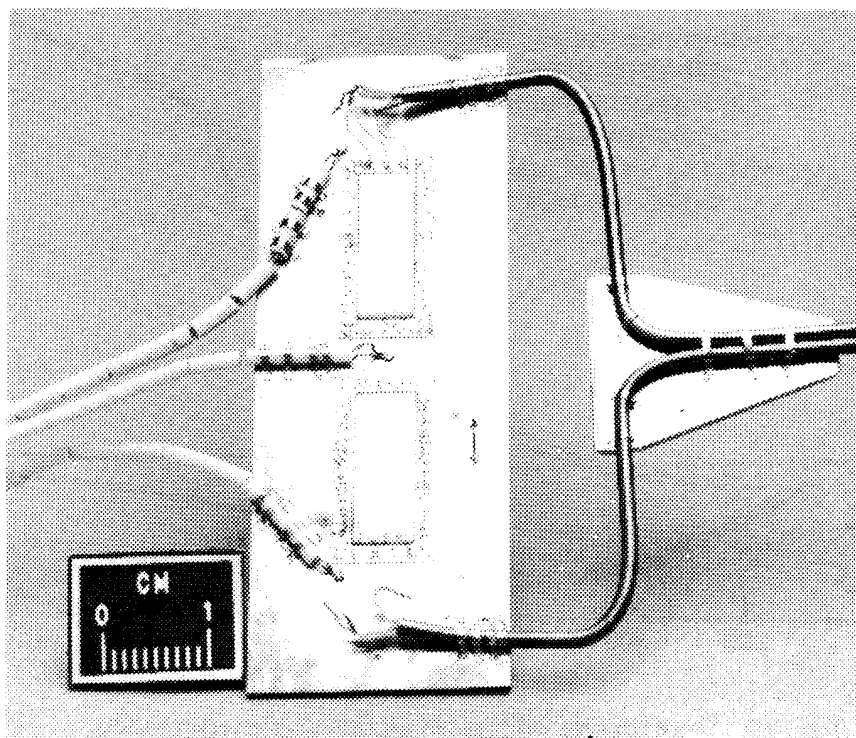also shows the effectiveness of these techniques for palladium-chromium and iron-chromium-aluminum gages.

Fig. 18. Two palladium-chromium weldable strain gages spot-welded on an SCS-6/Beta 21S TMC [0,90,0].

6.4. Instream Flow-Field Methods

Pitot rakes can be used to measure instream flow conditions but probably must be cooled for most applications. Figure 20 shows a new concept being developed for intrusive flow-field measurements (Graves et al. 1993). A retractable rake must be used to avoid disturbing the flow at critical operation points. Expendable probes, designed to burn off after a few seconds of pretest measurements, are also an option. Fiber optic microphones, which operate with a frequency response to 100 kHz with a dynamic acoustic range of 130 to 190 dB, are being developed for operation at 2000 °F. Figure 21 shows small skin friction devices. Chadwick and Schetz (1992) describe development of these small devices for use in engine combustor and nozzle applications.

Nonintrusive laser diagnostics have been in routine use for 25 or more years in the ground laboratory environment. Only recently, however, have efforts been underway to adapt these methods to flight. Cooling, size, and ruggedness to survive shock and vibration are being pinpointed for solutions for flight application. Instream laser measurement capabilities include flow velocity, temperature, density components, and flow chemical constituency measurements.

Figure 22 shows a laser absorption system being developed for in-flight measurements. Cavolowsky and Newfield (1992) describe this developmental technique for measuring engine combustor exit flow-field constituents. These constituents include the hydroxyl (OH) radical, water vapor, and oxygen to determine combustor efficiency.
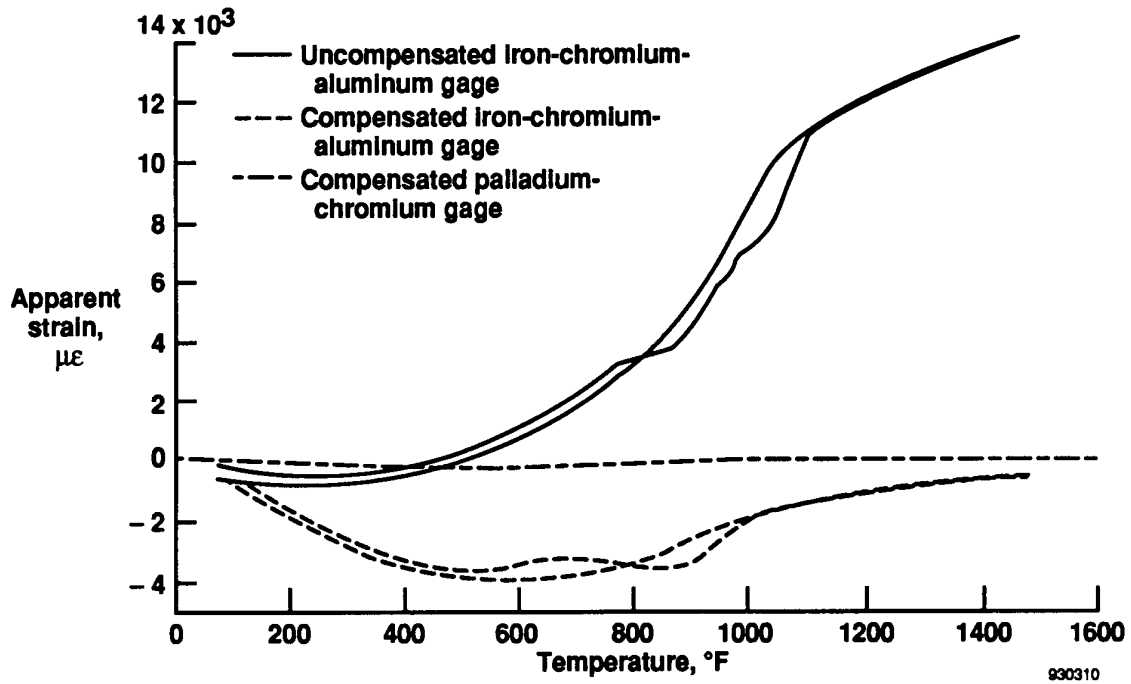
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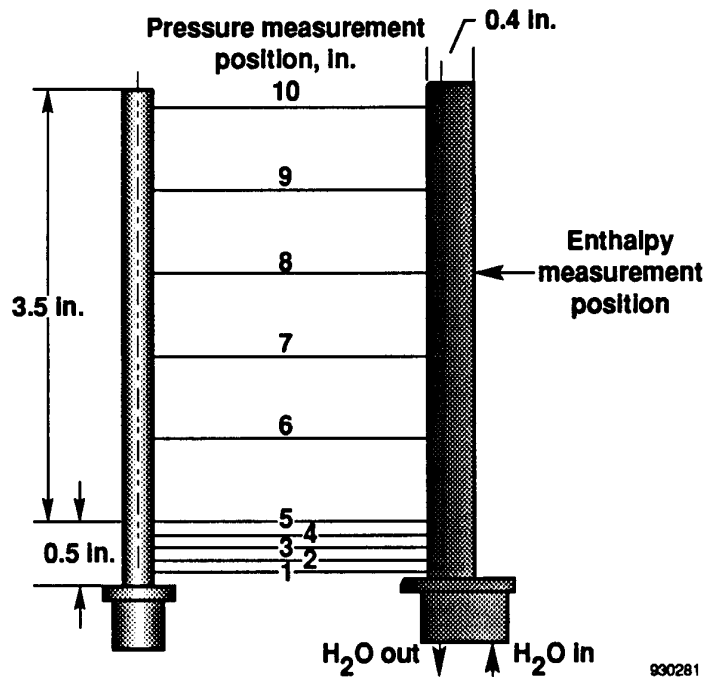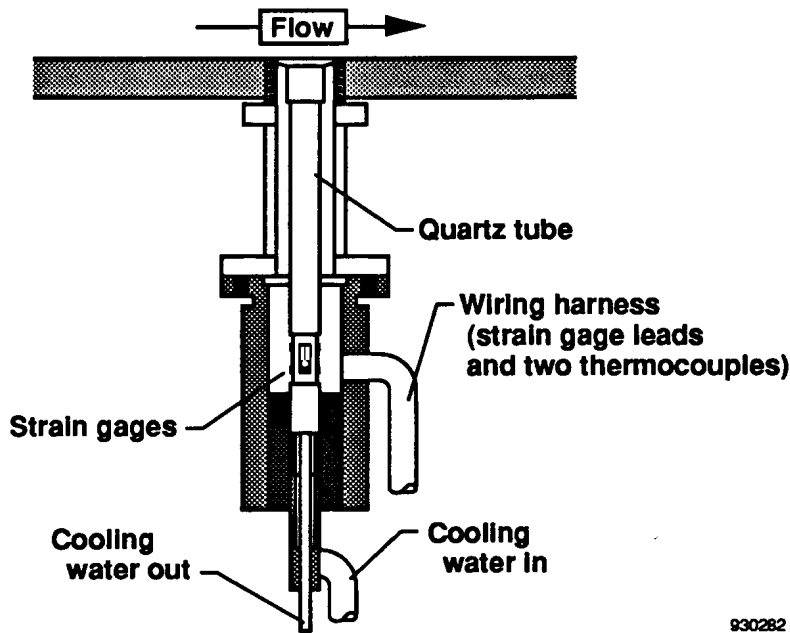Fig. 19. Temperature effects on strain gage performance.

Fig. 20. Probeless boundary rake (modified from Graves et al. 1993).

Fig. 21. Skin friction balance, DCAF 2ed DCAF entry design (Chadwick and Schetz 1992).

6.5. Airdata Techniques

Airdata measurements of Mach number or velocity, angles of attack and sideslip, altitude or ambient pressure, ambient temperature, and dynamic pressure or density are key to evaluating and controlling airbreathing flight vehicles. Potential measurement systems include robust onboard inertial and pressure systems. These data can be combined with data from remote radar tracking or satellite global positioning system (GPS) for vehicle position data. Another valuable source of airdata is balloon-borne (rawinsonde) sensing of ambient pressure and temperature and of local winds. Standard pitot-static methods for measuring airspeed and altitude and traditional techniques for measuring angles using deflection vanes or pitot-statics no longer apply at hypersonic speeds because of heating, aerodynamic, and pneumatic lag problems. Additionally, accuracy of these older methods needs improving in several instances. Angle-of-attack measurements for flight control and system testing provides an excellent example of this need.

Figure 23 shows scramjet thrust and mass flow sensitivity to changing angle of attack. As little as a 0.1° change in angle of attack can cause a 1 percent change in thrust because of the corresponding change in captured airflow at the inlet. Standard angle-of-attack measurement accuracy for subsonic-to-supersonic aircraft is ±0.25°. Today, hypersonic flight not only needs a reliable way to measure angle of attack but also needs to measure this angle to an accuracy level of ±0.1°. A sensitivity analysis would, likewise, show similar accuracy improvement requirements for Mach number and altitude.

7. INTERNATIONAL FLIGHT TEST CONCEPTS

Subsections 7.1 through 7.5 survey current work in hypersonic flight testing in the United States, France, Germany, Japan, and Russia. This survey illustrates the wide range of approaches and possibilities which exist for technical contributions from the flight test arena.

(a) Probe layout.

Fiberoptic pitch assembly

Optical fiber

Collimating lens

Fused silica windows

Laser light

Filter

Focusing lens

5 in.

Photodiode detector

Detector catch assembly

(b) Fiberoptic and detector assemblies.

Detector and lens assemblies

Inlet flow

Optical fibers

(c) Inlet probe configuration.

Combustor exit

Nozzle section

930283

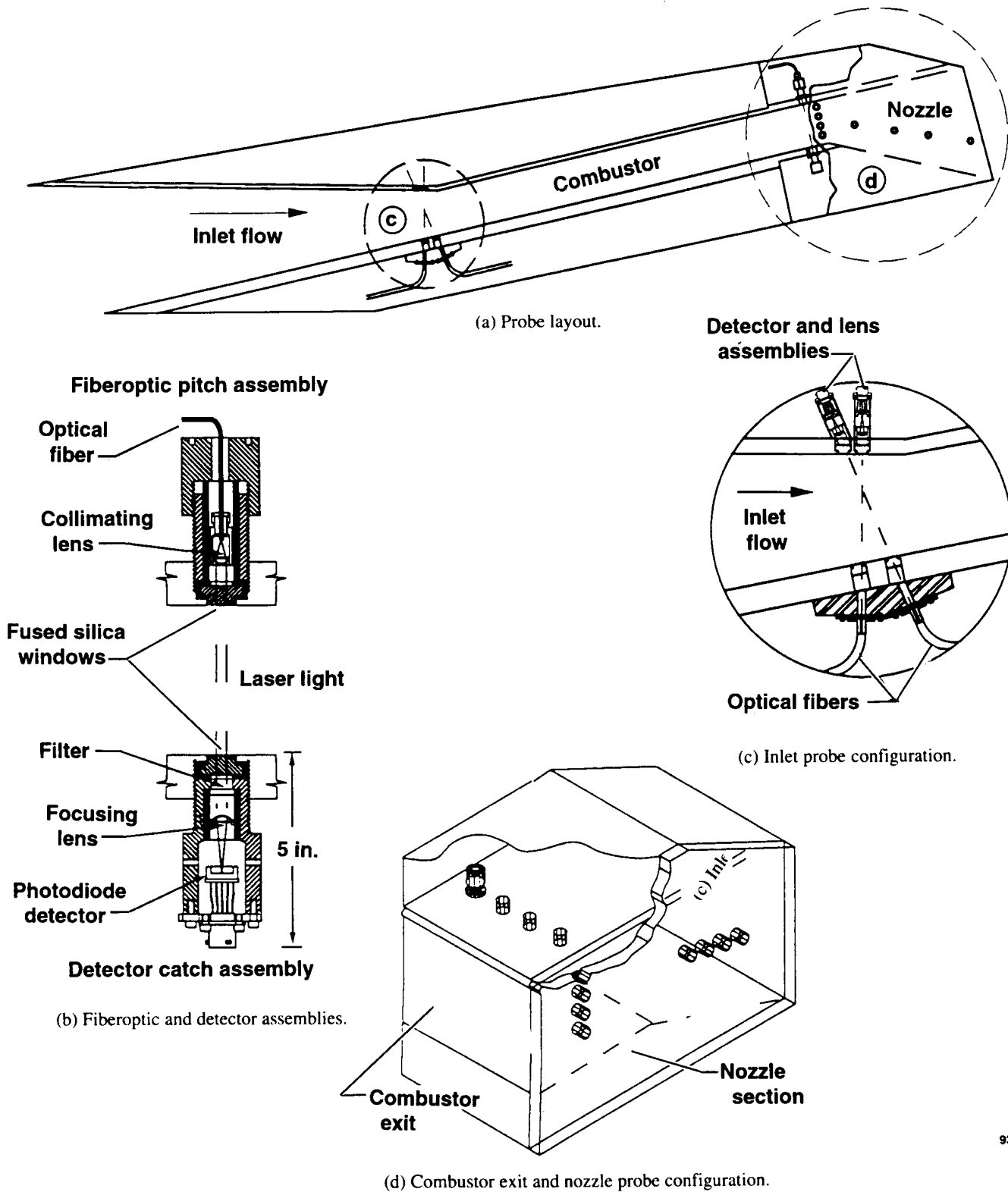(d) Combustor exit and nozzle probe configuration.

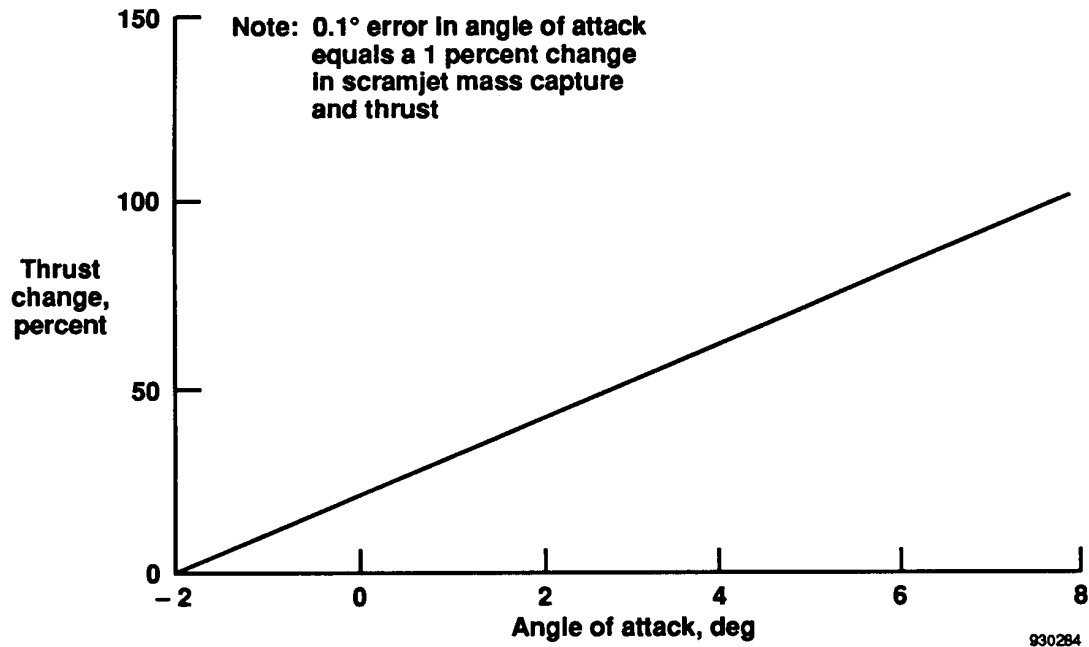Fig. 22. Optical probes in scramjet model.

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Fig. 23. Scramjet thrust sensitivity to changes in angle of attack at Mach 10.

7.1. United States

The United States has a relatively long history of hypersonic flight research. This history dates back to the X-15 aircraft and other projects of the 1950's and 1960's. (See section 2.) These hypersonic flight test programs centered on developing ramjets, unpowered vehicle aerodynamics and aerothermo-dynamics, materials, guidance and control, and instrumentation sensors, such as those required for the space shuttle. More recent examples of this flight test experience include the Sandia National Laboratory (Albuquerque, New Mexico) Sandia Winged Energetic Reentry Vehicle Experiment vehicle (Williamson 1992) and the ARPA and NASA joint program with Orbital Sciences Corporation aboard the Pegasus® rocket launch program (Curry, Meyer, and Budd 1992).

The National Aero-Space Plane Program has been developing plans for possible flight tests. These plans involve the supersonic external burning experiment with a captive-carry device aboard the SR-71A aircraft. Another proposal involves captive-carry experimental packages to be launched to hypervelocity Mach numbers aboard Minuteman II missiles. NASA and others have conducted numerous studies using the SR-71A aircraft as a supersonic launch platform for hypersonic research vehicles.

7.2. France

France's recent start on a scramjet development program is known as PREPHA (Debout 1991; Debout and Mathieu 1992) and is presently focused on a ground test development phase. As a partnership between the French government and industry, PREPHA is part of a national program which examines conceptual two-stage-to-orbit (TSTO) and SSTO approaches to a low Earth orbit space transportation system. This national partnership is funded by the Ministry of Defense and consists of the government

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agency, ONERA, the aerospace firms of Aerospatiale, Dassault, and the Hyperspace engine consortium of SNECMA and SEP.

The PREPHA objectives focus on scramjet propulsion development at hypersonic velocities up to approximately Mach 8 to 10. Initially, ground test facilities with engine components and subscale engine models will be used. The French have a strong interest in flight test development. Studies by Falempin et al. (1992) were conducted to define future engine flight test programs, but specifics are not available now.

7.3. Germany

Recent flight test studies in support of the German Aerospace Company (DASA) Saenger program have centered on manned and unmanned flight testbed vehicles for subscale versions of its turboramjet. Kuczera and Hauck (1992) and pl (1991) provide detailed descriptions of these studies. In brief, the genesis program known as the Hypersonic Technology Experiment (HYTEX) was examined in various forms. These forms ranged from manned horizontal takeoff to unmanned supersonic launch aboard such aircraft as the NASA SR-71A. Such an aircraft could air-launch a HYTEX derivative supersonically to study turbojet-to-ramjet mode operation and transition or air-launch at Mach 3 to start and operate the ramjet mode. Figure 24 shows some of the engine testbed flight test vehicle concepts. Studies are continuing on into the new extended phase I program. Funding for these studies is from the German Federal Ministry of Research and Technology (BMFT).

7.4. Japan

The National Aerospace Laboratory (NAL), National Space Development Agency (NASDA), and Institute of Space and Astronautical Science (ISAS) of Japan have investigated advanced hypersonic airbreathing technologies since the mid-1980's. Plans include subscale flight test development of aerodynamic, aerothermodynamic, composite materials, and control technologies. These plans are being pursued through such flight concepts as the NASDA H-2 Orbiting Plane (HOPE), Orbital Reentry Experiment (OREX), and ISAS Highly Maneuverable Experimental Spaceplane (HIMES). These experimental vehicles are to be launched from rockets for orbital reentry to automated, unmanned landing recoveries. Additionally, ISAS conducted small-scale helicopter drop model tests of the HIMES vehicle for landing tests in 1986 and 1987 (Inatani, Kawaguchi, and Yonemoto 1990) with a balloon-rocket launch of a reentry test flight in 1992 (Inatani et al. 1992).

Plans are also underway for a near-future joint NAL and NASDA flight test of automated landing using a small-scale HOPE vehicle dropped from a helicopter. This project is designated ALEX for Automatic Landing Experiment. Yamanaka (1992) discusses these and other plans for rocket-launched experiments, including an air-turboramjet engine concept.

The air-turboramjet (ATREX-500) and scramjet Liquid-Air Cycle Engine (LACE) propulsion developments are currently focused on ground tests, but future flight tests of subscale engines are also being considered. Such flight tests will probably follow Japan's preference for using unmanned, rocket-launched, free-flight, experimental vehicles as engine testbeds.
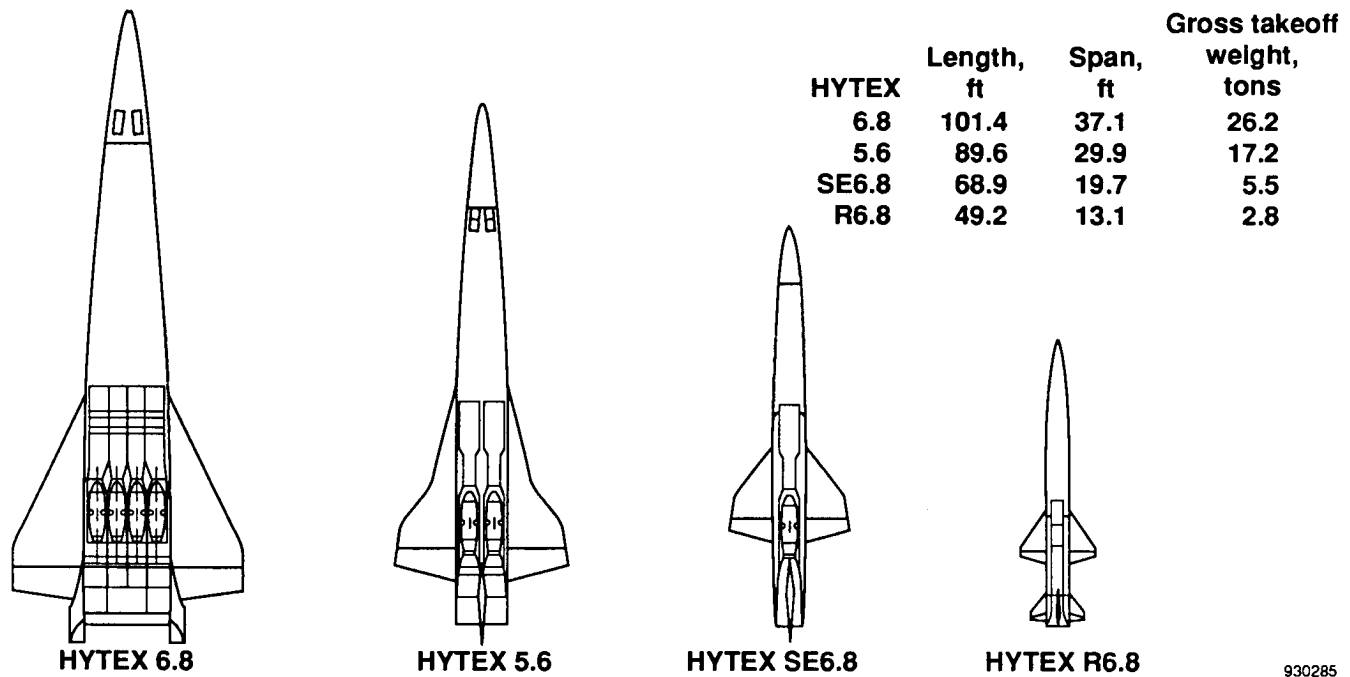
HYTEX	Length, ft	Span, ft	Gross takeoff weight, tons
6.8	101.4	37.1	26.2
5.6	89.6	29.9	17.2
SE6.8	68.9	19.7	5.5
R6.8	49.2	13.1	2.8

HYTEX 6.8   **HYTEX 5.6**   **HYTEX SE6.8**   **HYTEX R6.8**   930285

Fig. 24. The DASA Saenger project HYTEX vehicle concepts.

7.5. Russia

Since approximately 1987, Russia's Central Institute of Aviation Motors (CIAM), headquartered near Moscow, has conducted captive-carry flight tests of a complete subscale axisymmetric dual-mode scramjet engine using the Hypersonic Flying Laboratory (HFL) (Kandebo 1992a). Five flight test articles similar to those shown in fig. 25 were designed to conduct tests between Mach 5 and 6 at altitudes from approximately 85,000 to 100,000 ft. These hydrogen-cooled and -fueled stainless steel
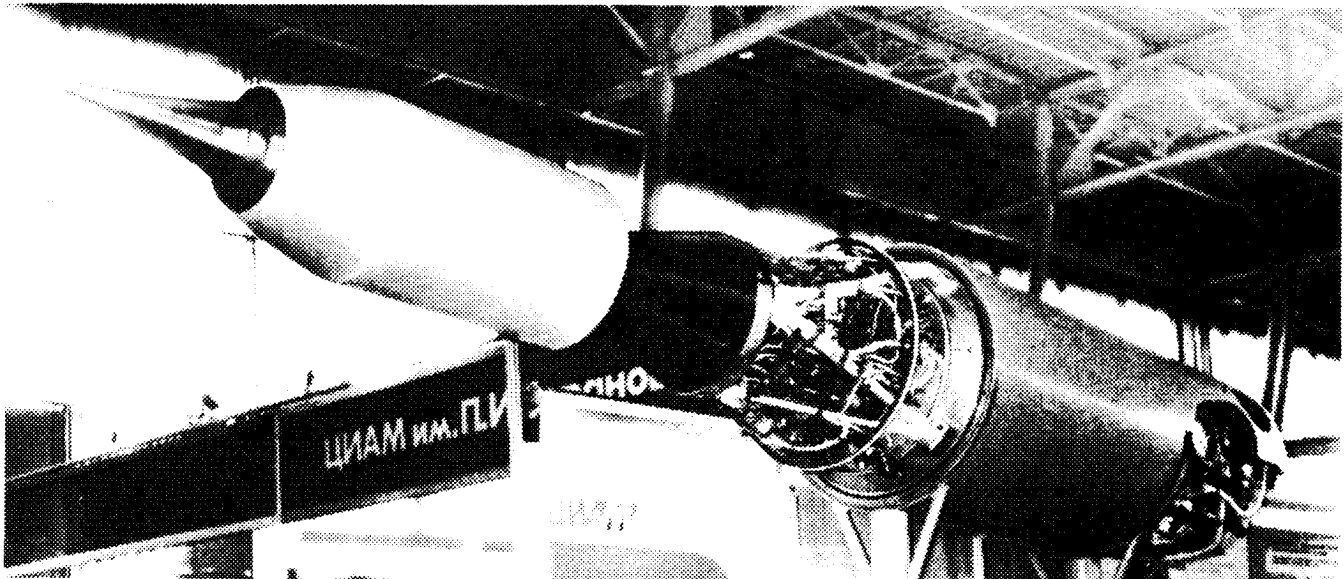

Fig. 25. Test flight articles.

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engines are approximately 4.20 ft long with an overall inlet diameter of 9 in. Three fuel injection stations with cavity flameholders perform ramjet or scramjet operations. Besides the engine, the HFL contains volume for the fuel and control gas tankage, control systems, and instrumentation package. The axisymmetric concept was selected to flight demonstrate supersonic combustion operation and was not used to directly measure thrust performance. This concept was also selected because it integrated well with the cylindrical launch rocket. Figure 26 shows the launch rocket which is flown on a depressed flight trajectory using a modified guidance and navigation system. To date, four of the five nonrecoverable engine configurations have been flown. These tests involved two nonoperating, cold-flow engines to evaluate the flight trajectory, vehicle integration, and system operation and two hot-flow flights with combustion operation. Instrumentation has been basic and confined to wall static pressure and thermocouple measurements with an emphasis on simple, robust systems to investigate supersonic combustion in real air.
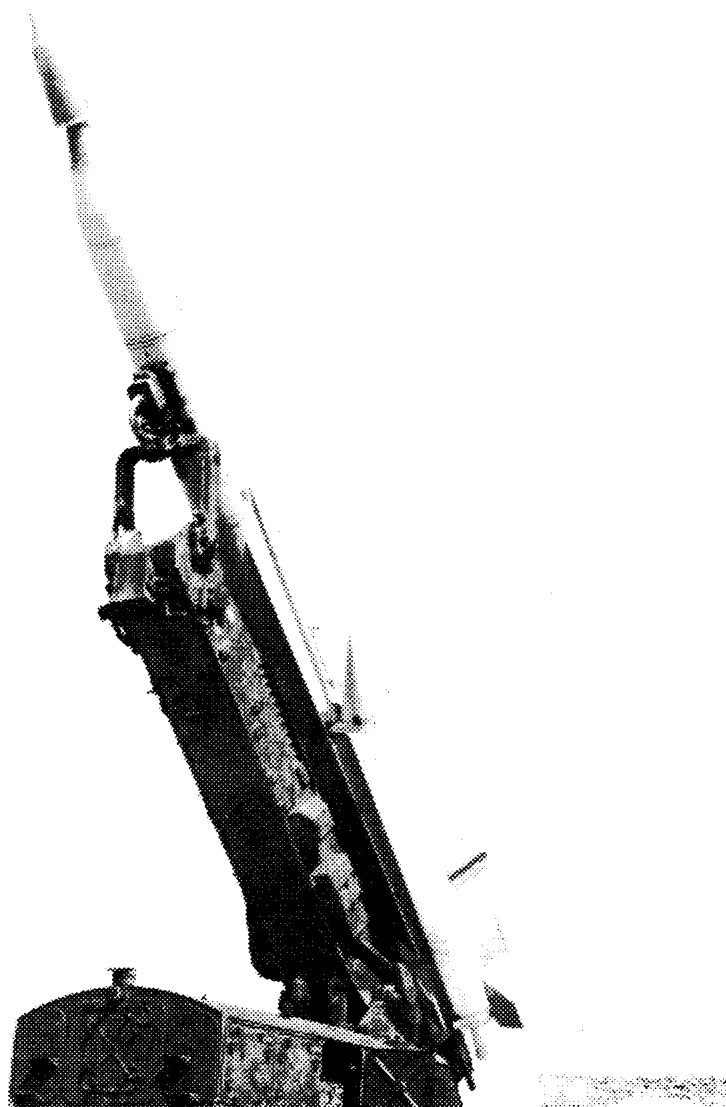

Fig. 26. Launch rocket with a modified guidance and navigation system.

To date, two successful hot-flow flights have been achieved at speeds from Mach 5.3 to 5.6 with reported sustained supersonic combustion times of 5 to 15 sec (Kandebo 1992b). CIAM plans to continue with such flight tests using axisymmetric and planar-compression subscale engines at Mach numbers up to, perhaps, 10.

8. CONCLUDING REMARKS

Nothing in the aeronautics discipline could be considered more difficult and challenging than hypersonic airbreathing flight. The exciting, yet sobering, realization is that, in spite of a 30-year developmental history, the scramjet-centered concept still has a long way to go before achieving practical atmospheric flight from above Mach 6 to low Earth orbit. The possibilities from global hypersonic cruise flight for commercial application to a low-cost space transportation system spur on world-wide competitive technology development in many industrial countries.

Such vehicles could provide quick, on-demand access to space with a payload; rapid turnaround capability; horizontal takeoff; other operational capabilities similar to those of aircraft; and rapid access to distant points on the Earth for commercial travel and other applications. These vehicles must be operationally reusable, reliable, safe, and cost effective and must have minimal negative environmental impact on the atmosphere.

To achieve those operational requirements, this class of airbreathing hypersonic vehicles requires a highly integrated airframe and propulsion system along with vehicle systems that operate in very hostile flight environments. These requirements are especially true for the scramjet engine. The needed hypersonic technology development is a complex, multifaceted problem compounded by limited ground test facilities and unvalidated design tools or methodologies. A careful blend of advanced analysis, ground test, and flight test is needed to design and develop these futuristic flight vehicles. Ultimate validation of any integrated flight vehicle system can only be achieved by careful flight test. Indeed, the flight arena is an indispensable aid in developing the individual technologies and design capabilities for that integrated vehicle.

The potential rewards are tremendous. On the other hand, high costs and programmatic risks, coupled with the complex, interrelated technical problems and lacking technologies, make this technology truly the last great frontier of aeronautics.

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13. ABSTRACT (Maximum 200 words)

Using the scramjet engine as the prime example of a hypersonic airbreathing concept, this paper reviews the history of and addresses the need for hypersonic flight tests. It also describes how such tests can contribute to the development of airbreathing technology. Aspects of captive-carry and free-flight concepts are compared. An incremental flight envelope expansion technique for manned flight vehicles is also described. Such critical issues as required instrumentation technology and proper scaling of experimental devices are addressed. Lastly, examples of international flight test approaches, existing programs, or concepts currently under study, development, or both, are given.

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